XIII. *Account of Experiments on Iron-built Ships, instituted for the purpose of discovering a correction for the deviation of the Compass produced by the Iron of the Ships. By* George Biddell Airy, *Esq. A.M., Astronomer Royal.*

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Section I.—*Preliminary.*

In the months of October and November 1835, a series of observations was made under the direction of the Board of Admiralty, by Commander Johnson, R.N., on the iron steam-ship Garry Owen, for ascertaining the amount of disturbance of the compass produced by the magnetic attraction of the iron, of which the ship's sides and bottom are composed. The details of these experiments are published in the Philosophical Transactions for 1836. Results of great importance were obtained as to the amount of deviation of the compass in different parts of the ship; and several remarkable experiments were described, which seemed to prove that the ship acted upon external compasses, in the manner of a permanent magnet. But no attempt was made to discover the laws of the magnetic disturbance, or to ascertain its causes; and no attempt could therefore be made to neutralize the ship's disturbing force by the introduction of new disturbing forces.

The last-mentioned point was, however, kept in sight by the Board of Admiralty, and partial arrangements were made for conducting a series of experiments referring expressly to this subject, whenever a favourable opportunity should occur. In the month of July 1838 the iron-built steam-ship the Rainbow was placed by the General Steam Navigation Company at the service of the Admiralty for magnetic examination. The conduct of the experiments was entrusted by the Board to me, and the vessel was immediately placed in the Basin of the Deptford Dock Yard.

The first point to be settled was the selection of stations in which the deviations of the compass should be observed. The object which I proposed to myself (the ascertaining the laws of the deviation, and the neutralization, if possible, of the deviating forces) made it a matter of no interest to me to try the action of the compass in many different places. I determined therefore on selecting only those in which it was likely that the compass, in the ordinary course of navigation, might be used for steering. With the assistance of Capt. Shirreff, R.N., Captain Superintendant of the Deptford Dock Yard, I fixed on the four following stations:

Station I., very near the binnacle as fixed in the ship, at the distance of 13 feet 2 inches from the extreme part of the stern.

Station II., at the place where the binnacle would probably be fixed in a steam-ship of the Royal Navy, at the distance of 31 feet 9 inches from the stern.

Station III., as near to the mizen-mast as observations could conveniently be made, distant 48 feet 3 inches from the stern.

Station IV., a short distance abaft the fore-mast, at the distance of 47 feet from the knight-head, or 151 feet 6 inches from the stern.

For the purpose of commanding a clear view above the engine-boxes and paddle-boxes, it was necessary to place in each of these positions a stage of considerable height (the elevation of its upper floor was 10 feet 2 inches). A lower floor was fixed in the stage at the elevation of 3 feet 6 inches above the deck; and upon this the azimuth compass used in the experiment was always placed. The elevation of its card above the deck was then about 4 feet $\frac{1}{2}$ inch. This elevation was adopted as coinciding almost exactly with that at which the compass was mounted in the binnacle when the ship was placed under my management.

The trouble of observing a compass upon the top of the stage was so small, that (although unimportant for the special objects of this inquiry) it was thought desirable to ascertain its error, as well as that of the lower compass, in each position of the vessel's head. In the observations of the first day the upper compass was placed upon the stage, with its card raised 10 feet 8 inches above the deck; it was afterwards raised 2 feet higher.

In adopting a method of observation, the following considerations were taken into account.

If we were certain that no sensible effect would be produced on the compass by the iron in the wharfs and the various buildings surrounding the basin, the easiest method of determining the error of the ship's compass would be to compare it with a compass on shore, either by reciprocal observations, or by observing with both the line of the ship's fore-mast and mizen-mast, or by observing with the ship's compass a mark at some distance, and observing with the shore compass the azimuth of the same mark when seen in the same line with the ship's compass. I omit the mention of a mark at so great a distance that its parallax in the movement of the ship would be insensible, because no very distant mark can be seen from the Deptford Dock Yard. But these methods require a general certainty that there are no local disturbing causes. The vessel had been placed so early in the basin, that I had had no opportunity of examining into the existence of local disturbances; and, as far as the general aspect of the localities could suggest an opinion, it was extremely probable that the local disturbances would be sensible. There are several iron posts, and an iron crane, very near the basin wall; there was a great mass of iron tanks in a shed adjoining it; and the great length of the ship brought the compass when at Station I. very near to one side or another of the basin. It appeared therefore best to observe the azimuth of a chimney on the opposite side of the river, with the ship's compass only, and to register the local position of the compass in such a manner that the correction depend-

ing upon its place in the basin might be taken from a map; and it was supposed that by afterwards carrying a compass round the basin when the ship was removed, observing with it the same chimney, and correcting for local position in the same manner, the amount of error depending on local disturbance might be found, and applied, if necessary, to the observations in the ship.

The observations were made in the following manner.

Through a hole in the upper floor of the stage a wooden spindle, $2\frac{1}{2}$ inches square, was passed. The lower end of this spindle was connected with a wooden fork, whose branches lodged upon the gimble-frame of the azimuth-compass, in such a manner that when the spindle was turned it carried with it the frame of the compass. At the upper end of the spindle was a small telescope with a thick wire in its field of view; the height of the telescope above the deck was about 15 feet 6 inches; so that a person standing on the upper floor of the stage could with the telescope conveniently observe the chimney above the paddle-boxes and engine-boxes, while a person below could read off the bearing by the azimuth compass in the usual way. At the beginning and at the end of each series, or at other convenient times, the bearing of the chimney was observed as well with the sights of the azimuth compass as with the telescope; and thus was obtained an index error of the telescope, by which all observations made with the telescope could be converted into equivalent observations with the compass sights.

Two theodolites were stationed at points commanding the chimney and every part of the basin. The duty of the theodolite observers was, at each position of the ship, to observe the wooden spindle placed on the compass, to observe the chimney, and to make reciprocal observations.

The person upon the top of the stage, having ascertained that the ship was steadily moored, directed that the ship's bell should be struck, as a signal to all the observers, and then gave out the ordinal number of the observation. This was entered by each of the observers in his book. The person on the stage directed his telescope to the chimney and gave notice thereof to the person below, who read off the compass and entered the reading in his book: then the person on the stage directed his telescope to the centre of the ship's funnel, and the compass in like manner was read by the person below: these observations were repeated; then the person at the top of the stage observed the chimney with the upper compass, and entered the reading in his book. During these observations, each of the theodolite-observers had twice observed the compass-spindle, the chimney, and the other theodolite, and entered the readings in his book; and other observations were made and entered by other persons, as will shortly be mentioned. Each observer gave signal of the completion of his observations by raising a flag: as soon as all had finished, the word was given for swinging the ship into a new position.

On the first two days of observation, July 26 and 30, a compass was placed upon one of the paddle-boxes, and the azimuth of the chimney was regularly observed with

it. The disturbances of the compass, however, appeared anomalous; and as it did not appear probable that this compass could be corrected so completely as the others, the observations were never wholly reduced.

In the first two days there were mounted on shore, near the western side of the basin, a dipping needle, and a two foot horizontal needle, suspended by a skein of silk, and carrying a reflector with which the divisions of a scale were observed in GAUSS's method; and near the south side of the basin a dipping needle, and a two foot horizontal needle transverse to the meridian, carried by two parallel skeins of silk in the manner of GAUSS and WEBER's bifilar magnetometer, and carrying a reflector with which a divided scale was observed. These were observed when the signal was given for the compass observations.

On the third day, July 31, three dipping needles were placed in the ship, in positions very near to the compass stations I. III. IV.: during one complete revolution of the ship they were placed so that the vibrations of the needle were in the plane of the keel; and during another complete revolution, they were so placed that the vibrations were transverse to the keel.

The same dipping needles were afterwards, on August 2, carried on shore, and arranged in a line nearly E. and W. for observation of the effect produced by bringing the ship's head and stern very near to the side of the basin while the keel was E. and W. They were then arranged in a N. and S. line, and the effects of the two extremities of the ship while the keel was N. and S. were examined.

The ship was then taken out of the basin, and on August 6 the same compass which had been used at the lower stage-floor in the four stations on board the ship, was mounted upon a stage carried by a raft (in the construction of which there was not much iron) and floated round the basin. The height of the compass above water was made nearly the same as the height of the lower stage floor (in the ship) above water; and the raft was carried to all parts where there was suspicion of local disturbance, care being taken that it should be placed nearly opposite each iron post, and nearly intermediate to adjacent posts.

On August 14 observations of horizontal intensity were made with a needle suspended by a silk fibre, at each of the four stations, the ship's head being placed successively N., W., S., and E.*, by means of a compass on shore.

On August 20 and August 22, after the application of correctors, observations of the compasses were made in the same manner as those made for ascertaining the amount of error, in order to verify the accuracy of the correction.

I have now only to give the names of the persons employed in the various parts of the operation.

The swinging the ship round was managed by Captain SHIRREFF or by Mr. MORRICE

* It is always to be understood that the cardinal points of the compass and the azimuths are referred to the *magnetic* meridian.

(Master Attendant of the Dock Yard), with the assistance of men attached to the Dock Yard.

The two theodolites (A. and B.) were assigned to Mr. James Glaisher and Mr. Ellis, Assistants at the Royal Observatory.

The western dipping needle and horizontal needle (C.) were observed, on July 26, by Professor Christie, and on July 30 by the Rev. R. Sheepshanks.

The southern dipping needle and horizontal needle transverse to the meridian (D.) were observed by the Rev. R. Main, First Assistant at the Royal Observatory.

The observations with the compass on the paddle-box (E.) were made by Captain Shirreff.

The upper telescope was directed and the upper compass (F.) read off by myself in the whole of the experiments.

The compass on the lower stage-floor (G.) was read off on July 26 by Lieutenant Denison, R.E., on July 30 by Francis Baily, Esq., and in all the subsequent observations by Captain Shirreff.

The compass on the raft (H.) was observed by Mr. Main, with the assistance of Captain Shirreff.

Of the three dipping-needles on board, on July 31, the sternmost was read by Captain Shirreff, and the other two by Mr. Main.

The dipping needles on shore, on August 2, were read by Mr. Main.

The observations of the time of vibration for horizontal intensity on August 14 were made by myself, with the assistance of Captain Shirreff.

To all the persons named above my most cordial thanks are due for the zeal and steadiness with which they followed out my plans under the most distressing circumstances of weather. But to Captain Shirreff in particular an acknowledgement of my obligations must here be given. Not only was the assistance of men and materials from the Dock Yard furnished by Captain Shirreff in the way which I thought most desirable, but by his presence and by the interest in the operations which he displayed, the services of all the subordinate persons were rendered fully efficient; while the part which he took as an active observer, from the beginning to the end, materially lightened my labours and increased my confidence in the results.

Section II.—*Immediate Results of Observations.*

I. Local disturbances of the compass, as shown by the observations on the Raft.

A plan of the Basin in Deptford Dock Yard was prepared, from simultaneous observations with the two theodolites A. and B., on a signal carried to different parts of the basin-wall, and was copied (by pricking off) for the insertion of the places of the compass in every series of observations. The positions of the compass when on the raft were laid down on one of these copies, from simultaneous observations with the theodolites, as already described. The positions from No. 105 to 114 range along the E. and S.E. side of the basin, from the entrance to the S. angle: 115, 116, and 117, are on the S.W. side between the ways of two building

slips; and the remainder, from 118 to 129, are on the N.W. side, from the W. angle to the entrance. The distance of the compass from the wharf varied from 16 to 24 feet. At each of these positions the chimney was observed with the compass. The next step (as in all the other observations) was to correct for locality, and this was done in the following manner. The angle at A, the south-eastern theodolite, between the chimney and the theodolite B. was 59° 29′, and the angle at B. between the chimney and A. was 113° 38′. Consequently the angle subtended by A B at the chimney was 6° 53′. The line A B being, therefore, supposed to represent 6° 53′, and being divided into portions corresponding each to 1°, commencing at B, dotted lines were drawn from the chimney through the points forming these divisions, and thus indicated the points in the basin at which the true azimuth of the chimney differs 1°, 2°, 3°, &c., from the azimuth observed at B. If then the correction + 1° be applied to the azimuths (reckoned from north through east, south, and west), as observed with the compass at any point in the dotted line marked + 1°, an azimuth will be obtained which ought to be the same as if it had been observed at B, and whose difference from that at B can be occasioned only by local disturbance; and similarly for positions of the compass upon any other dotted lines. For intermediate positions the correction was taken to 5′ by inspection. In this manner the following Table was formed.

No. of observation.	Observed azimuth reduced to B.	Mean of all the observed azimuths reduced.	Apparent local disturbance.	No. of observation.	Observed azimuth reduced to B.	Mean of all the observed azimuths reduced.	Apparent local disturbance.
105	37° 25′	37° 46′	−0° 21′	118	38° 45′	37° 46′	+0° 59′
106	37 10		−0 36	119	38 35		+0 49
107	38 5		+0 19	120	38 10		+0 24
108	36 30		−1 16	121	38 10		+0 24
109	37 30		−0 16	122	37 0		−0 46
110	37 45		−0 1	123	38 5		+0 19
111	37 45		−0 1	124	38 0		+0 14
112	37 40		−0 6	125	38 25		+0 39
113	37 45		−0 1	126	37 35		−0 11
114	37 40		−0 6	127	35 55		−1 51
115	38 5		+0 19	128	39 0		+1 14
116	38 15		+0 29	129	37 5		−0 41
117	37 55		+0 9				

The magnitude of these disturbances is so small as to leave it almost doubtful whether any correction ought to be applied for them. There is evidently no need for correction when the place of the compass is far removed from the side of the basin, as it was in all positions of the compass except at Station I. The only instances of the observations at Station I. in which corrections for local disturbance are applied are the following:

Nos. 1, 2, 3, 4, 6, 8, (nearly in the position of 105) + 0° 20′ each.
No. 24 (near the place of 119). . . . . − 0° 50′ each.
No. 25 (between 120 and 121). . . . . − 0° 25′ each.
No. 33 (near 106) . . . . + 0° 30′ each.

II. Azimuths of the ship's head and disturbance of the compass on the lower stage floor at Station I.

The chimney having been observed with the telescope carried by the spindle mounted on the compass, the reading of the compass card was at first expressed in the azimuths or amplitudes used by nautical men. This was then converted into azimuth reckoned from the N. through the E., S., and W., to N. proceeding from 0° to 360°. Then the correction for index error of the telescope was applied: then the correction for locality, and then (if necessary) the correction for local disturbance. The azimuth thus corrected would have been 37° 46′, had the ship caused no disturbance. The excess of the corrected azimuth above 37° 46′ is set down as the disturbance of the compass by the ship; the sign + denotes that the azimuth appears too great, or that the needle is deflected to the left.

The funnel of the steam-ship having been observed in the same way, its apparent azimuth, as affected by the ship's disturbance of the compass, was found in the same manner (omitting the correction for locality): correcting this for the disturbance (already found), the true azimuth was obtained.

In this manner the following table was formed.

No. of observation.	True azimuth of ship's head.	Disturbance of compass.	No. of observation.	True azimuth of ship's head.	Disturbance of compass.
	° ′	° ′		° ′	° ′
1	203 5	−16 50	19	1 35	+40 45
2	214 53	−22 45	20	19 25	+51 20
3	220 0	−23 20	21	38 25	+50 50
4	230 0	−30 5	22	57 45	+46 30
5	240 50	−34 5	23	76 55	+39 15
6	248 50	−36 40	24	93 10	+33 5
8	256 4	−40 2	25	109 0	+26 40
9	267 44	−44 27	26	125 50	+19 40
10	276 12	−47 50	27	142 10	+11 55
11	282 57	−49 27	28	159 10	+ 4 20
12	292 17	−52 25	29	171 5	− 1 35
13	294 0	−53 45	30	189 45	−11 0
14	300 35	−54 50	31	202 5	−16 45
15	308 0	−53 50	32	220 25	−25 10
16	313 47	−54 2	33	248 55	−37 50
17	321 40	−50 10	34	278 15	−48 25
18	338 25	−33 0			

No. 7. was inadvertently omitted in the numeration. It will be remarked that the general positions of the vessel's head from No. 1 to 11 coincide nearly with those from No. 30 to 34. The following points are worthy of attention; 1st, that between Nos. 18 and 19, upon changing the position of the vessel's head 23°, the disturbance was altered 74°, so that the change of the vessel's position appeared on the compass card to be nearly 97°; 2nd, that the maximum of the positive errors is distinctly less than the maximum of the negative errors. The latter remark will be found to bear in an important degree on the theoretical explanation of the errors.

III. Disturbance of the compass on the lower stage floor at Station II.

The operation is in every respect the same as the last, except that no correction was applied for local disturbance.

No. of observation.	True azimuth of ship's head.	Disturbance of compass.	No. of observation.	True azimuth of ship's head.	Disturbance of compass.
	° ′	° ′		° ′	° ′
35	282 51	−21 36	45	103 36	+12 54
36	300 4	−12 41	46	124 26	+ 7 26
37	320 49	− 1 19	47	143 57	+ 1 26
38	340 7	+ 9 31	48	163 16	− 4 16
39	353 48	+15 4	49	179 6	− 9 6
40	11 26	+18 34	50	203 1	−16 16
41	31 14	+19 46	51	222 21	−21 51
42	49 47	+19 51	52	244 56	−26 26
43	67 3	+18 12	53	267 46	−24 16
44	85 1	+14 59			

IV. Disturbance of the compass on the lower stage-floor at Station II., when the steam was up and the boilers and engine hot.

No. of observation.	True azimuth of ship's head.	Disturbance of compass.	No. of observation.	True azimuth of ship's head.	Disturbance of compass.
	° ′	° ′		° ′	° ′
90	279 1	−21 31	98	99 11	+15 19
91	296 36	−13 6	99	115 26	+11 4
92	315 54	− 4 54	100	143 26	+ 3 4
93	329 6	+ 3 54	101	174 21	− 6 21
94	354 26	+12 34	102	218 26	−20 26
95	14 36	+16 54	103	246 41	−23 11
96	37 41	+19 49	104	275 1	−26 1
97	62 26	+18 34			

If these disturbances and those of the last Table be constructed graphically, the azimuth being taken as abscissa, and the disturbance of the compass as ordinate, and if a curve in each case be drawn through the points, it will be found that the curves do not sensibly differ. It appears therefore that no sensible part of the disturbance depends on the state of heat of the engines.

V. Disturbance of the Compass on the Lower Stage Floor at Station III.

No. of observation.	True azimuth of ship's head.	Disturbance of compass.	No. of observation.	True azimuth of ship's head.	Disturbance of compass.
	° ′	° ′		° ′	° ′
54	(274 11)	− 19 41	64	93 11	+ 11 49
55	(310 24)	− 13 24	65	120 36	+ 7 54
56	311 18	− 4 18	66	139 46	+ 3 44
57	324 26	+ 2 49	67	163 9	− 3 9
58	340 51	+ 7 39	68	187 9	− 10 39
59	2 34	+ 11 56	69	216 6	− 18 21
60	22 16	+ 14 29	70	235 11	− 21 41
61	38 11	+ 16 19	71	259 59	− 24 29
62	60 34	+ 15 26	72	275 41	− 21 41
63	81 36	+ 13 24			

It is conjectured that the azimuth in No. 54 ought to be increased 10°, and that in No. 55 ought to be diminished 10°; and the subsequent calculations are made on this supposition.

VI. Disturbance of the Compass on the Lower Stage Floor at Station IV.

No. of observation.	True azimuth of ship's head.	Disturbance of compass.	No. of observation.	True azimuth of ship's head.	Disturbance of compass.
	° ′	° ′		° ′	° ′
73	276 21	− 9 21	82	95 6	+ 7 9
74	291 6	− 2 6	83	130 6	+ 3 54
75	321 6	+ 0 24	84	146 46	− 0 46
76	330 36	+ 8 54	85	170 16	− 6 16
77	347 6	+ 8 54	86	198 1	− 12 31
78	3 41	+ 9 49	87	219 36	− 15 21
79	16 46	+ 10 14	88	245 9	− 15 39
80	49 54	+ 7 36	89	264 34	− 12 4
81	66 59	+ 8 1			

The azimuth or the disturbance in No. 75 appears to be wrong. It is not used in the subsequent calculations.

(To avoid confusion, I shall defer to a subsequent part of this paper the account of the disturbance of the compass on the upper stage floor.)

VII. Times of Vibration of a Needle suspended by a Silk Fibre near the Level of the Lower Stage Floor.

		s
On shore 30 vibrations were performed in	. . . .	140·6
At Station I.,	the ship's head being N., the time of 30 vibrations was .	300·5
	the ship's head being E., the time of 30 vibrations was .	119·5
	the ship's head being S., the time of 30 vibrations was .	103·6
	the ship's head being W., the time of 30 vibrations was .	133·9
At Station II.,	the ship's head being N., the time of 30 vibrations was .	166·3
	the ship's head being E., the time of 30 vibrations was .	129·7
	the ship's head being S., the time of 30 vibrations was .	120·8
	the ship's head being W., the time of 30 vibrations was .	157·3
At Station III.,	the ship's head being N., the time of 30 vibrations was .	153·4
	the ship's head being E., the time of 30 vibrations was .	130·2
	the ship's head being S., the time of 30 vibrations was .	121·7
	the ship's head being W., the time of 30 vibrations was .	158·5
At Station IV.,	the ship's head being N., the time of 30 vibrations was .	147·8
	the ship's head being E., the time of 30 vibrations was .	130·7
	the ship's head being S., the time of 30 vibrations was .	128·8
	the ship's head being W., the time of 30 vibrations was .	172·3

VIII. Observations with Dipping Needles on board the Ship, near the Level of the Stage Floor at Stations I., III., IV., the Needles vibrating in the Vertical Plane passing through the Ship's Keel.

(The dipping-needle employed at Station I. is a small needle of very fine workmanship, by DOLLOND, lent by Mr. DOLLOND for the experiments. Its dip on shore appeared to be 72° 40′.

The dipping-needle used at Station III. is a larger needle, by JONES, lent by Mr. CHRISTIE. Its dip on shore was about 69° 10′.

The dipping-needle employed at Station IV. is an excellent needle belonging to the Admiralty, made by DOLLOND, of intermediate dimensions. Its dip on shore was about 69° 35′.)

The letter H denotes that the dip was towards the head, S that it was towards the stern. When the number of degrees exceeds 90° the needle is dipping on the side of the vertical, opposite to that denoted by a number of degrees less than 90.

No. of observation.	Azimuth of ship's head.	Dip at Station I.	Dip at Station III.	Dip at Station IV.
35	282° 51′	78° 50′ S.	89° 35′ H.	89° 20′ H.
36	300 4	....	83 21	79 55
37	320 49	87 20 S.	78 0	78 42
38	340 7	89 25 H.	72 6	69 10
39	353 48	88 10	71 37	68 10
40	11 26	88 5 H.	71 55	67 12
41	31 14	89 10 S.	74 47	68 32
42	49 47	86 10	79 45	65 17
43	67 3	82 30	84 59	85 35 H.
44	85 1	78 20	92 18 H.	88 20 S.
45	103 36	72 15	79 3 S.	78 50
46	124 26	68 0	71 53	67 0
47	143 57	64 55	66 58	61 30
48	163 16	61 50	63 28	58 25
49	179 6	61 5	62 28	58 10
50	203 1	61 50	63 55	58 30
51	222 21	64 40	68 40	68 22
52	244 56	68 35	75 10	69 5
53	267 46	74 5 S.	83 43 S.	79 32 S.

IX. Observations with dipping-needles near the level of the stage-floor at Stations I., III., IV.; the needles vibrating in the vertical plane transverse to the ship's keel.

(The needles are the same as those used in the last experiments.) The letter S. denotes that the dip was to the starboard, L. that it was to the larboard.

No. of observation.	Azimuth of ship's head.	Dip at Station I.	Dip at Station III.	Dip at Station IV.
54	284° 11′	78° 30′ S.	74° 45′ S.	70° 2′ S.
55	300 24	79 25	76 16	70 32
56	311 18	83 30	78 15	77 25
57	324 26	85 30	81 30 S.	80 58
58	340 51	89 5 S.	.. ..	87 58 S.
59	2 34	86 0 L.	.. ..	82 15 L.
60	22 16	80 0	79 16 L.	69 38
61	38 11	76 15	73 26	68 57
62	60 34	72 40	68 8	61 40
63	81 36	69 10	66 29	60 45
64	93 11	71 0	66 15	60 42
65	120 36	72 30	68 54	62 25
66	139 46	76 0	73 56	63 40
67	163 9	78 55	79 30	72 52
68	187 9	87 40 L.	89 3 L.	89 50 L.
69	216 6	85 0 S.	82 12 S.	83 45 S.
70	235 11	81 35	77 50	73 25
71	259 59	78 55	74 32	69 40
72	275 41	78 30 S.	74 40 S.	69 40 S.

(The observations with the dipping-needle and large magnets on shore will be deferred to another part of this paper.)

Section III.—*Theory of Induced Magnetism.*

The fundamental supposition of the theory on which I shall found the calculations in the following pages is, that, by the action of terrestrial magnetism, every particle of iron is converted into a magnet whose direction is parallel to that of the dipping-needle, and whose intensity is proportional to the intensity of terrestrial magnetism: the upper end having the property of attracting the north end of the needle, and the lower end that of repelling it.

It would have been desirable to make the calculations on Poisson's theory, which undoubtedly possesses greater claims on our attention, as a theory representing acurately the facts of some very peculiar cases, than any other. The difficulties, however, in the application of that theory to complicated cases, are great, perhaps insuperable. And in ordinary cases, the simpler theory that I have mentioned will give the same comparative though not the same absolute results. For instance, Poisson's theory explains the near equality between the attraction of a sphere or thick shell and that of a thin shell: the simpler theory does not explain this near equality; but

the shell being given, it enables us to compute its comparative effects in different positions as well as POISSON'S. In the case of a spheroidal mass of iron, the result is similar. And as far as giving a general agreement between the results of calculation and the comparative effects of given masses in different positions, the theory appears sufficiently accurate.

Let the place of the compass be the origin of co-ordinates: let A be the azimuth of the ship's head, measured from the magnetic north towards the east: a the azimuth of any particle measured from the ship's head; so that A + a is the azimuth of that particle from the north. Let b be the angular depression of the particle. Then if r be the distance of the particle from the compass; x, y, z, the ordinates towards the north, towards the east, and vertically downwards; we shall have

$$x = r \,.\, \cos b \,.\, \cos \overline{\mathrm{A} + a}, \qquad y = r \,.\, \cos b \,.\, \sin \overline{\mathrm{A} + a}, \qquad z = r \,.\, \sin b.$$

Let I represent the intensity of terrestrial magnetism, δ the dip, m a constant depending on the mass of the particle, 2 l the length of the small magnet into which it is changed. Then the ordinates of that end of the small magnet which attracts the north end of the needle will be

$$x - l \cos \delta, \qquad y, \qquad z \quad l \sin \delta.$$

Its distance (omitting the squares, &c. of l) = $\sqrt{\{r^2 - 2\,l x \cos\delta - 2\,l z \sin\delta\}}$

$$= r - \frac{l}{r}(x \cos\delta + z \sin\delta).$$

And the resolved parts of its attraction (supposing the whole attraction inversely as the n^{th} power of the distance) will be—In the direction of x,

$$\mathrm{I}\, m \frac{x - l\cos\delta}{\left\{r - \frac{l}{r}(x\cos\delta + z\sin\delta)\right\}^{n+1}}$$

$$= \mathrm{I}\, m \,.\, \frac{x}{r^{n+1}} \left\{1 - l \,.\, \frac{\cos\delta}{x} + l \,.\, \overline{n+1} \,.\, \frac{x\cos\delta + z\sin\delta}{r^2}\right\}.$$

In the direction of y,

$$\mathrm{I}\, m \frac{y}{\left\{r - \frac{l}{r}(x\cos\delta + z\sin\delta)\right\}^{n+1}}$$

$$= \mathrm{I}\, m \frac{y}{r^{n+1}} \left\{1 + l \,.\, \overline{n+1} \,.\, \frac{x\cos\delta + z\sin\delta}{r^2}\right\}.$$

In the direction of z,

$$\mathrm{I}\, m \frac{z - l\sin\delta}{\left\{r - \frac{l}{r}(x\cos\delta + z\sin\delta)\right\}^{n+1}}$$

$$= \mathrm{I}\, m \,.\, \frac{z}{r^{n+1}} \left\{1 - l \,.\, \frac{\sin\delta}{z} + l \,.\, \overline{n+1} \,.\, \frac{x\cos\delta + z\sin\delta}{r^2}\right\}.$$

In like manner, the repulsive force produced by the other end of the small magnet will be—In the direction of x

$$= \mathrm{I}\, m \frac{x}{r^{n+1}} \left\{ 1 + l . \frac{\cos \delta}{x} - l . \overline{n+1} . \frac{x \cos \delta + z \sin \delta}{r^2} \right\}.$$

In the direction of y

$$= \mathrm{I}\, m \frac{y}{r^{n+1}} \left\{ 1 - l . \overline{n+1} . \frac{x \cos \delta + z \sin \delta}{r^2} \right\}.$$

In the direction of z

$$= \mathrm{I}\, m . \frac{z}{r^{n+1}} \left\{ 1 + l . \frac{\sin \delta}{z} - l . \overline{n+1} . \frac{x \cos \delta + z \sin \delta}{r^2} \right\}.$$

The difference between the attractive and repulsive forces, or the true disturbing force, will be—In the direction of x,

$$- \mathrm{I} \cos \delta . \frac{2\, l m}{r^{n+1}} + \mathrm{I} \cos \delta . \frac{2 . \overline{n+1} . l m . x^2}{r^{n+3}} + \mathrm{I} \sin \delta . \frac{2 . \overline{n+1} . l m . x z}{r^{n+3}}.$$

In the direction of y,

$$\mathrm{I} \cos \delta . \frac{2 . \overline{n+1} . l m . x y}{r^{n+3}} + \mathrm{I} \sin \delta . \frac{2 . \overline{n+1} . l m . y z}{r^{n+3}}.$$

In the direction of z,

$$- \mathrm{I} \sin \delta . \frac{2\, l m}{r^{n+1}} + \mathrm{I} \cos \delta . \frac{2 . \overline{n+1} . l m . x z}{r^{n+3}} + \mathrm{I} \sin \delta . \frac{2 . \overline{n+1} . l m . z^2}{r^{n+3}}.$$

These are expressions for the disturbing forces produced by a single particle. To find the disturbing forces produced by the whole of the iron in the ship, we must take the sum of these expressions for every particle in the ship. Expressing this summation by the letter S, we have the whole disturbing forces as follows:

In the direction of x,

$$- \mathrm{I} \cos \delta . \mathrm{S} \frac{2\, l m}{r^{n+1}} + \mathrm{I} \cos \delta . \mathrm{S} \frac{2 . \overline{n+1} . l m . x^2}{r^{n+3}} + \mathrm{I} \sin \delta . \mathrm{S} \frac{2 . \overline{n+1} . l m . x z}{r^{n+3}}.$$

In the direction of y,

$$\mathrm{I} \cos \delta . \mathrm{S} \frac{2 . \overline{n+1} . l m . x y}{r^{n+3}} + \mathrm{I} \sin \delta . \mathrm{S} \frac{2 . \overline{n+1} . l m . y z}{r^{n+3}}.$$

In the direction of z,

$$- \mathrm{I} \sin \delta . \mathrm{S} \frac{2\, l m}{r^{n+1}} + \mathrm{I} \cos \delta . \mathrm{S} \frac{2 . \overline{n+1} . l m . x z}{r^{n+3}} + \mathrm{I} \sin \delta . \mathrm{S} \frac{2 . \overline{n+1} . l m . z^2}{r^{n+3}}.$$

We will now transform these formulæ by substituting for x, y, and z, their values in terms of r, A, a, and b. And we will suppose the compass to be in the vertical plane passing through the ship's keel, and the arrangement of the iron on both sides of that plane to be symmetrical. Then

$$\frac{x^2}{r^{n+3}} = \frac{\cos^2 b . \cos^2 \overline{\mathrm{A}+a}}{r^{n+1}} = \frac{1}{2} \frac{\cos^2 b}{r^{n+1}} + \frac{1}{2} \frac{\cos^2 b}{r^{n+1}} (\cos 2\,\mathrm{A} . \cos 2\,a - \sin 2\,\mathrm{A} . \sin 2\,a).$$

But

$$\text{S}\,\frac{l\,m\cos^2 b\,.\sin 2\,\text{A}\,.\sin 2\,a}{r^{n+1}},\ \text{or}\ \sin 2\,\text{A}\,.\,\text{S}\,\frac{l\,m\cos^2 b\,.\sin 2\,a}{r^{n+1}},$$

will evidently $= 0$, because for the same value of l, m, b, and r, there will be two values of a, one positive and the other negative. Hence the term

$$\text{S}\,\frac{2\,.\,\overline{n+1}\,.\,l\,m\,.\,x^2}{r^{n+3}}$$

will become

$$\overline{n+1}\,.\,\text{S}\,\frac{l\,m\,.\cos^2 b}{r^{n+1}} + \cos 2\,\text{A}\,.\,\overline{n+1}\,.\,\text{S}\,\frac{l\,m\,.\cos^2 b\,.\cos 2\,a}{r^{n+1}}.$$

The value of $\frac{x\,z}{r^{n+3}}$ is

$$\frac{\sin b\,.\cos b\,.(\cos \text{A}\,.\cos a - \sin \text{A}\,.\sin a)}{r^{n+1}}$$

in which, for the same reason, the term sin A . sin a is to be rejected. Hence the term

$$\text{S}\,\frac{2\,.\,\overline{n+1}\,.\,l\,m\,.\,x\,z}{r^{n+3}}$$

will become

$$\cos \text{A}\,.\,2\,.\,\overline{n+1}\,.\,\text{S}\,\frac{l\,m\,.\sin b\,.\cos b\,.\cos a}{r^{n+1}}.$$

The value of $\frac{x\,y}{r^{n+3}}$ is

$$\frac{1}{2}\,\frac{\cos^2 b\,(\sin 2\,\text{A}\,.\cos 2\,a + \cos 2\,\text{A}\,.\sin 2\,a)}{r^{n+1}}.$$

Hence the term

$$\text{S}\,\frac{2\,.\,\overline{n+1}\,.\,l\,m\,.\,x\,y}{r^{n+3}}$$

will become

$$\sin 2\,\text{A}\,.\,\overline{n+1}\,.\,\text{S}\,\frac{l\,m\,.\cos^2 b\,.\cos 2\,a}{r^{n+1}}.$$

The value of $\frac{y\,z}{r^{n+3}}$ is

$$\frac{\sin b\,.\cos b\,(\sin \text{A}\,.\cos a + \cos \text{A}\,.\sin a)}{r^{n+1}}.$$

Hence the term

$$\text{S}\,\frac{2\,.\,\overline{n+1}\,.\,l\,m\,.\,y\,z}{r^{n+3}}$$

will become

$$\sin \text{A}\,.\,2\,.\,\overline{n+1}\,.\,\text{S}\,\frac{l\,m\,.\sin b\,.\cos b\,.\cos a}{r^{n+1}}.$$

The value of $\frac{z^2}{r^{n+3}}$ is $\frac{\sin^2 b}{r^{n+1}}$, which admits of no further reduction.

Hence the expressions for the whole disturbing forces are,—In the direction of x,

$$- \mathrm{I}\cos\delta \left\{ \mathrm{S}\,\frac{2\,lm}{r^{n+1}} - \overline{n+1}\,.\,\mathrm{S}\,\frac{lm\,.\cos^2 b}{r^{n+1}} \right\} + \mathrm{I}\cos\delta\,.\cos 2\mathrm{A}\,.\overline{n+1}\,.\,\mathrm{S}\,\frac{lm\cos^2 b\,.\cos 2a}{r^{n+1}}$$

$$+ \mathrm{I}\sin\delta\,.\,\cos\mathrm{A}\,.\,2\,.\overline{n+1}\,.\,\mathrm{S}\,\frac{lm\,.\sin b\,.\cos b\,.\cos a}{r^{n+1}}.$$

In the direction of y,

$$\mathrm{I}\cos\delta\,.\sin 2\mathrm{A}\,.\overline{n+1}\,.\mathrm{S}\,\frac{lm\,.\cos^2 b\,.\cos 2a}{r^{n+1}} + \mathrm{I}\sin\delta\,.\sin\mathrm{A}\,.\,2\,.\overline{n+1}\,.\mathrm{S}\,\frac{lm.\sin b\,.\cos b.\cos a}{r^{n+1}}$$

In the direction of z,

$$-\mathrm{I}\sin\delta.\left\{\mathrm{S}\,\frac{2\,lm}{r^{n+1}} - 2\,.\overline{n+1}\,.\mathrm{S}\,\frac{lm\,.\sin^2 b}{r^{n+1}}\right\} + \mathrm{I}\cos\delta\,.\cos\mathrm{A}.2.\overline{n+1}\,.\,\mathrm{S}\,\frac{lm.\sin b.\cos b.\cos a}{r^{n+1}}.$$

Let

$$\mathrm{S}\,\frac{2\,lm}{r^{n+1}} - \overline{n+1}\,.\mathrm{S}\,\frac{lm\,.\cos^2 b}{r^{n+1}} = \mathrm{M}$$

$$2\,.\overline{n+1}\,.\mathrm{S}\,\frac{lm\,.\sin b\,.\cos b\,.\cos a}{r^{n+1}} = \mathrm{N}$$

$$\overline{n+1}\,.\mathrm{S}\,\frac{lm\,.\cos^2 b\,.\cos 2a}{r^{n+1}} = \mathrm{P}$$

$$\mathrm{S}\,\frac{2\,lm}{r^{n+1}} - 2\,.\overline{n+1}\,.\mathrm{S}\,\frac{lm\,.\sin^2 b}{r^{n+1}} = \mathrm{Q}.$$

The four quantities M, N, P, Q, are then constant, depending solely upon the construction of the ship, not changing with any variations of terrestrial locality, or of magnetic dip or intensity. Then the disturbing forces (always estimated by their action on the north or marked end of the needle) are

Towards the magnetic north $- \mathrm{I}\cos\delta\,.\mathrm{M} + \mathrm{I}\cos\delta\,.\mathrm{P}\,.\cos 2\mathrm{A} + \mathrm{I}\sin\delta\,.\mathrm{N}\,.\cos\mathrm{A}$.

Towards the magnetic east . $\mathrm{I}\cos\delta\,.\mathrm{P}\,.\sin 2\mathrm{A} + \mathrm{I}\sin\delta\,.\mathrm{N}\,.\sin\mathrm{A}$.

Vertically downwards. . . $- \mathrm{I}\sin\delta\,.\mathrm{Q} + \mathrm{I}\cos\delta\,.\mathrm{N}\,.\cos\mathrm{A}$.

Before transforming these into another shape, we will consider the construction which they indicate as proper for the correction of a compass disturbed by the induced magnetism only of the iron in a ship.

The only force which it is necessary to destroy is that directed to the east, or

$$\mathrm{I}\cos\delta\,.\mathrm{P}\,.\sin 2\mathrm{A} + \mathrm{I}\sin\delta\,.\mathrm{N}\,.\sin\mathrm{A}.$$

In the usual cases (at least for wood-built ships) P and N will both have positive values; the iron being supposed to lie almost entirely on one side of the compass (so that $\cos a$ and $\cos 2a$ are almost always positive), and being almost entirely at a lower level than the compass (so that $\sin b \cos b$ is almost always positive).

Suppose now we find a mass of iron, which when placed at a certain distance and a certain depression, and in the same azimuth as the ship's head, will produce the same disturbance of the compass. (This is the method of determining the distance, &c. for Barlow's plate.) Then this mass, in the azimuth A, produces the disturbing

force to the east, $I \cos \delta . P . \sin 2 A + I \sin \delta . N . \sin A$; and therefore in the azimuth A' it produces the disturbing force to the east, $I \cos \delta . P . \sin 2 A' + I \sin \delta . N . \sin A'$. Suppose now that the mass is placed towards the stern of the ship (or on the side opposite to that in which the ship's iron is, for the most part, situated), but at the same distance and depression as those already determined. (This is the rule for applying BARLOW's plate as a partial corrector.) A' must now be made $= A + 180°$; and the disturbing force produced by the mass is now $I \cos \delta . P . \sin 2 A - I \sin \delta . N . \sin A$. Combining this with the disturbing force produced by the ship's iron, the compound force is reduced to $2 I \cos \delta . P . \sin 2 A$; that is, one of the terms expressing the disturbing force is destroyed, and the other is doubled. Whether this change of the force is advantageous or prejudicial, will depend not only on the value of δ (the dip), but also on the proportion between the values of N and P (that is, on the way in which the iron is distributed with regard to elevation above or depression below the compass, and with regard to the manner in which it surrounds the compass).

Let us consider, for instance, the case of a long wood-built steam-boat, with a compass on deck or in a cabin. It is probable that the iron of the engines and funnel may be pretty equally distributed above and below the level of the compass. Here $\sin b . \cos b$ has as many negative as positive values, and therefore $N = 0$. But $\cos 2 a$ is always positive, because the azimuth of any part of the iron from the vertical plane passing through the keel does not amount to 45°, and therefore P is positive. Consequently in this instance the application of BARLOW's plate doubles the error of the compass.

Yet it is possible in any case to destroy the disturbing force entirely. Suppose that BARLOW's plate is fixed as above mentioned, and that the disturbing force is therefore $2 I \cos \delta . P . \sin 2 A$. Now let a second mass of iron be introduced, with its centre at the same level as the compass, and in the azimuth A''. The general expression for the force which it produces is

$$I \cos \delta . P'' . \sin 2 A'' + I \sin \delta . N'' . \sin A''.$$

But $N'' = 0$ (because there are as many negative values of $\sin b . \cos b$ as there are positive). Combining this, then, with the force produced by the ship's iron and by the BARLOW's plate already mounted, the whole force is

$$I \cos \delta . (2 P . \sin 2 A + P'' . \sin 2 A'').$$

Now this quantity may be made $= 0$ by making $A'' = A \pm 90°$, and $P'' = 2 P$; for then

$$\sin 2 A'' = \sin (2 A \pm 180°) = - \sin 2 A,$$

and the second factor becomes

$$2 P . \sin 2 A - 2 P . \sin 2 A.$$

Hence we get the following simple rule for the perfect correction of the compass.

1. Determine the position of BARLOW's plate, with regard to the compass, which

will produce the same effect as the iron in the ship. (It will be sufficient if when placed on the E. side it produces the same effect as the ship when the ship's head is E.)

2. Fix Barlow's plate at the distance and depression determined by the last experiment, but in the opposite azimuth (or towards the ship's stern).

3. Mount another mass of iron at the same level as the compass, but on the starboard or larboard side, and determine its position so that the compass shall point correctly when the ship's head is N.E., S.E., S.W., or N.W.

Then the compass will be correct in all positions of the ship's head, and in all magnetic latitudes.

When the disturbing iron of the ship is at the same level as the compass, the correction is much more simple. It is only necessary then to introduce a single mass of iron at the starboard or larboard side, and at the same level as the compass. For the ship's disturbing force is then

$$I \cos \delta \,.\, P \,.\, \sin 2\, A,$$

and the force produced by this mass is

$$I \cos \delta \,.\, P'' \,.\, \sin 2\, A'' ;$$

and if $A'' = A \pm 90°$, the sum of these terms will be 0, provided $P'' = P$, the distance for which condition will be easily ascertained by experiment.

In general it may be remarked, that if one mass of iron is placed exactly opposite another equal mass, both in azimuth and in elevation, it doubles its disturbing effect; if one mass be placed opposite the other in azimuth and at the same elevation or depression, or if it be placed in the same azimuth but with elevation instead of depression, or *vice versâ*, it destroys that term of the disturbance which depends on sin A, and doubles that which depends on sin 2 A. And if one mass be placed at the same level as the compass, its effects may be destroyed by placing another mass at the same level, in azimuth differing 90° on either side. (This conclusion, for spherical masses, was also obtained by Poisson.) To this we may add, that if a disturbance, from whatever cause arising, follows the law of $+ \sin 2\, A$ (changing sign in the successive quadrants, and positive when the ship's head is between N. and E.), it may be destroyed by placing a mass of iron on the starboard or larboard side, at the same level as the compass; if it follows the law of $- \sin 2\, A$, the mass of iron must be on the fore or aft side.

The form of Barlow's plate appears objectionable, in so far as having its broad side turned towards the compass, it occupies a considerable arc of azimuth, and $\cos 2\, a$ may therefore (for some parts of it) be small or negative. A plate of iron rolled into a scroll, and placed with its end directed towards the compass, appears better; but I prefer a long box filled with iron chain, as less likely to possess the permanent magnetism, from which no plate iron is free; its end should be directed towards the compass.

I trust that in the preceding remarks on the imperfection of Barlow's plate as a

corrector, I shall not appear to have treated Mr. BARLOW's construction with harshness. I can truly assert that my feelings and my intentions are of a very different character. To Mr. BARLOW we are indebted for almost all the experimental knowledge which we possess on the subject of the disturbance produced by masses of iron; the use of his plate *as a corrector* was avowedly proposed by him as imperfect; and it requires no great experience in the pursuit of experimental and practical philosophy to learn to venerate the man who makes the first step in devising a construction applicable to a given purpose. I must not omit to add, that Mr. BARLOW's plate corrects that part of the disturbance which is most important in the most critical circumstances, namely, in the high magnetic latitudes. Without Mr. BARLOW's proposed construction I should never have arrived at the more perfect construction described above; with it the invention of something more perfect was easy.

We will now resume the consideration of the expressions for the disturbing forces produced by the ship.

The first term in the expression for the disturbance towards the north is constant. It appears therefore that if M be positive, the absolute directive force on the needle will be, on the whole, diminished. On examining the expression for M it will be seen that its value is greatest (for a given mass of iron at a given distance) when the iron is immediately above or below the compass, and that it is least when the iron is at the same level as the compass. It is proper therefore that both in the construction of the ship and in the fixing of correctors, no large mass of iron should be placed below the compass.

The expression for disturbing force towards the ship's head is,

$$\cos A \times \text{force towards north} + \sin A \times \text{force towards east,}$$

$$= I \cos \delta \,.\, (-M + P) \cos A + I \sin \delta \,.\, N.$$

The second term of this expression is independent of the position of the ship, and therefore cannot be distinguished, in experiments made at any one locality, from permanent magnetism. But as it contains the factor $I \sin \delta$, or the vertical force of terrestrial magnetism, it may be discovered from experiments made in different localities, where the magnitude of the vertical force differs much.

The expression for the disturbing force towards the starboard side of the ship is

$$\cos A \times \text{force towards east} - \sin A \times \text{force towards north,}$$

$$= I \cos \delta \,.\, (M + P) \sin A.$$

It will be convenient to remember that M is the coefficient on which the absolute diminution of the directive force depends; that N is the coefficient upon which depends the force similar to permanent magnetism; and that P is the coefficient upon which depends the transversal force changing sign in the successive quadrants of azimuth.

It will also be convenient to remember that M is largest when the mass of iron is below, and may be negative if the mass of iron is nearly at the same level; that N

will vanish if the mass of iron is nearly at the same level as the compass, or may vanish from the opposition of different masses in azimuth while their depression is similar; and that P will vanish if the mass of iron is below, or may vanish from the opposition of effect produced by masses in azimuths differing 90°, but that masses in opposite azimuths combine to increase P.

It may now be desirable to consider the modifications produced in the horizontal forces by the heeling of the ship. The pitching causes a variation in the position of the keel alternately in one direction and in the opposite, and its effects may therefore probably be neglected; but the heeling frequently continues in the same direction for many hours or days, and therefore it will not be safe to omit it. To simplify our expressions, we will suppose the angle of heel to be not very great.

Let the different particles of the ship be referred to the place of the compass by means of the angles a and b as before, but let a be the azimuth of any particle from the direction of the ship's keel as measured in a plane parallel to that of the deck, and let b be the angle of depression as measured, from the plane parallel to the deck, towards the line which is normal to the deck. Then a and b are independent of the ship's heeling. Let h be the angle of heel towards the starboard side; and suppose h so small that its square may be neglected. Then we have

$$x = r \,.\, \cos b \,.\, \cos a \,.\, \cos \mathrm{A} - r \,.\, \cos b \,.\, \sin a \,.\, \sin \mathrm{A} + \sin h \,.\, r \,.\, \sin b \,.\, \sin \mathrm{A}.$$

$$y = r \,.\, \cos b \,.\, \cos a \,.\, \sin \mathrm{A} + r \,.\, \cos b \,.\, \sin a \,.\, \cos \mathrm{A} - \sin h \,.\, r \,.\, \sin b \,.\, \cos \mathrm{A}.$$

$$z = r \,.\, \sin b + \sin h \,.\, r \,.\, \cos b \,.\, \sin a.$$

The new term introduced into x^2 is

$$\sin h \,.\, 2\, r^2 \{\sin b \,.\, \cos b \,.\, \cos a \,.\, \sin \mathrm{A} \,.\, \cos \mathrm{A} - \sin b \,.\, \cos b \,.\, \sin a \,.\, \sin^2 \mathrm{A}\},$$

and therefore the new term introduced into

$$\mathrm{I} \cos \delta \,.\, \mathrm{S}\, \frac{2 \,.\, \overline{n+1} \,.\, l m \,.\, x^2}{r^{n+3}}$$

will be

$$\sin h \,.\, \mathrm{I} \cos \delta \,.\, \sin 2\,\mathrm{A} \,.\, \mathrm{S}\, \frac{2 \,.\, \overline{n+1} \,.\, l m \,.\, \sin b \,.\, \cos b \,.\, \cos a}{r^{n+1}} = \sin h \,.\, \mathrm{I} \cos \delta \,.\, \mathrm{N} \,.\, \sin 2\,\mathrm{A}.$$

The new term introduced into $x\,z$ will be

$$\sin h \,.\, r^2 \{\cos^2 b \,.\, \sin a \,.\, \cos a \,.\, \cos \mathrm{A} - \cos^2 b \,.\, \sin^2 a \,.\, \sin \mathrm{A} + \sin^2 b \,.\, \sin \mathrm{A}\},$$

and therefore the new term introduced into

$$\mathrm{I} \sin \delta \,.\, \mathrm{S}\, \frac{2 \,.\, \overline{n+1} \,.\, l m \,.\, x\, z}{r^{n+3}}$$

will be

$$\sin h \,.\, \mathrm{I} \sin \delta \,.\, \sin \mathrm{A} \,.\, \mathrm{S}\, \frac{2 \,.\, \overline{n+1} \,.\, l m \,.\, (\sin^2 b - \cos^2 b \,.\, \sin^2 a)}{r^{n+1}}.$$

Let

$$\mathrm{S}\, \frac{2 \,.\, \overline{n+1} \,.\, l m\, (\sin^2 b - \cos^2 b \,.\, \sin^2 a)}{r^{n+1}} = \mathrm{R};$$

(it is easily seen that $R = M + P - Q$); then the new term introduced into

$$I \sin \delta \,.\, S \frac{2 \,.\, \overline{n+1} \,.\, lm \,.\, xz}{r^{n+3}} \text{ is}$$

$$\sin h \,.\, I \sin \delta \,.\, R \,.\, \sin A.$$

Hence the whole addition to the force towards the magnetic north is

$$\sin h \,.\, I \cos \delta \,.\, N \,.\, \sin 2A + \sin h \,.\, I \sin \delta \,.\, R \,.\, \sin A.$$

The new term introduced into xy is

$$\sin h \,.\, r^2 \{-\sin b \,.\, \cos b \,.\, \cos a (\cos^2 A - \sin^2 A) + 2 \sin b \,.\, \cos b \,.\, \sin a \,.\, \sin A \,.\, \cos A\},$$

and therefore the new term introduced into

$$I \cos \delta \,.\, S \frac{2 \,.\, \overline{n+1} \,.\, lm \,.\, xy}{r^{n+3}}$$

will be

$$-\sin h \,.\, I \cos \delta \,.\, \cos 2A \,.\, S \frac{2 \,.\, \overline{n+1} \,.\, lm \,.\, \sin b \,.\, \cos b \,.\, \cos a}{r^{n+1}} = -\sin h \,.\, I \cos \delta \,.\, N \,.\, \cos 2A.$$

The new term introduced into yz is

$$\sin h \,.\, r^2 \{\cos^2 b \,.\, \sin a \,.\, \cos a \,.\, \sin A + \cos^2 b \,.\, \sin^2 a \,.\, \cos A - \sin^2 b \,.\, \cos A\},$$

and therefore the new term introduced into

$$I \sin \delta \,.\, S \frac{2 \,.\, \overline{n+1} \,.\, lm \,.\, yz}{r^{n+3}}$$

will be

$$\sin h \,.\, I \sin \delta \,.\, \cos A \,.\, S \frac{2 \,.\, \overline{n+1} \,.\, lm \,.\, (\cos^2 b \,.\, \sin^2 a - \sin^2 b)}{r^{n+1}} = -\sin h \,.\, I \sin \delta \,.\, R \cos A.$$

Hence the whole addition to the force towards the magnetic east is

$$-\sin h \,.\, I \cos \delta \,.\, N \,.\, \cos 2A - \sin h \,.\, I \sin \delta \,.\, R \,.\, \cos A.$$

Combining the expressions just found with those found in the first investigation of forces, we have the following:

Whole disturbing force to magnetic north $= -I \cos \delta \,.\, M + I \cos \delta \,.\, P \,.\, \cos 2A$
$+ I \sin \delta \,.\, N \,.\, \cos A + \sin h \{I \cos \delta \,.\, N \,.\, \sin 2A + I \sin \delta \,.\, R \,.\, \sin A\}$.

Whole disturbing force to magnetic east $= I \cos \delta \,.\, P \,.\, \sin 2A + I \sin \delta \,.\, N \,.\, \sin A$
$+ \sin h \,.\, \{-I \cos \delta \,.\, N \,.\, \cos 2A - I \sin \delta \,.\, R \,.\, \cos A\}$.

Transforming these into expressions for the forces in directions related to the direction of the ship's keel, we have

Whole disturbing force towards ship's head

$$= -I \cos \delta \,.\, M \,.\, \cos A + I \cos \delta \,.\, P \,.\, \cos A + I \sin \delta \,.\, N + \sin h \,.\, I \cos \delta \,.\, N \,.\, \sin \,.\, A.$$

Whole disturbing force in the horizontal plane, towards the starboard side

$$= I \cos \delta \,.\, M \,.\, \sin A + I \cos \delta \,.\, P \,.\, \sin A + \sin h \{-I \cos \delta \,.\, N \,.\, \cos A - I \sin \delta \,.\, R\}.$$

We have already shown how the terms independent of h (except those multiplied

by M) may be neutralized. One part of the operation was, to place aft the compass a mass of iron which if in front of the compass would have given the same value of N which the ship gives. Now when this mass of iron is fixed aft, we may either regard it as an additional part of the ship in the same azimuth A and having the same angle of heel h, but giving a constant N negative in magnitude by reason of the factor $\cos a = \cos 180°$ which enters into its formation; or we may regard it as a new mass, with positive coefficient N, with azimuth A + 180°, with angle of heel $-h$, and whose action is estimated in the resulting expressions as towards the azimuth A + 180° or from the ship's head. In either way of considering it, we find that by the process for neutralizing the term depending on N when the ship is not heeling, we have also neutralized the terms depending on N when the ship is heeling: and these terms may at once be put out of consideration. The only term, therefore, which remains to be considered is the following:

Disturbing force in the horizontal plane towards the starboard side, depending on the ship's heeling, $= - \sin h \, . \, \mathrm{I} \sin \delta \, . \, \mathrm{R}$.

For the *general* correction of this term, no easy method suggests itself. But the following considerations may serve to show the probability that constructions already proposed for another purpose will in a great measure correct it. First, with regard to the order of magnitude of this term; as $\mathrm{R} = \mathrm{M} + \mathrm{P} - \mathrm{Q}$, it is a term of the same order as the others which occur in this investigation (before multiplication by the factor $\sin h$), and therefore such masses of iron as those which are competent to correct the other terms may be expected to be of sufficient magnitude, with proper arrangement, to correct this term. Next, with regard to its law as depending on the position of the particles of iron: R is positive if $\sin^2 b$ exceeds $\cos^2 b \, . \, \sin^2 a$: but $r \, . \, \sin b$ is the depression of any particle below the compass measured perpendicularly to the deck, and $r \, . \, \cos b \, . \, \sin a$ is the ordinate measured from the plane passing through the keel and masts towards the starboard side. Hence we find this rule. If a line parallel to the keel be drawn through the compass, and if two planes be drawn through this line, inclined at angles of 45° to the plane passing through the masts and keel, so that a transverse section of the ship at any place present the section X: then all the iron in the upper and lower angles tends to increase R, and all the iron in the starboard and larboard angles tends to diminish R.

The principal part of the ship's iron will probably be in the lower angle, and will, therefore, tend to make R positive. Now we have, for correction of the term P, proposed to place a mass of iron on the starboard or larboard side, at the same level as the compass. It is evident that this iron tends to make R negative, and, therefore, tends to correct the effect of the ship's iron in disturbing the compass while the ship is heeling. Whether by varying the position of the mass of iron used to neutralize N, and thereby varying the magnitude both of P and of R, it may be practicable to make this lateral mass of iron neutralize both P and R, I cannot say. If it be impracticable, the accurate neutralization of P is evidently to be secured in preference

to that of R. In any case, however, it will be possible to neutralize R, or the remaining part of R, for any given magnetic latitude, by placing a magnet in a position perpendicular to the ship's deck, and with its centre at the same level as the centre of the compass. To secure rigorously the latter condition, the place of the magnet should be fore or aft the compass. If we suppose the marked end of the magnet to be downwards, its action downwards parallel to the mast may be represented by $-V'$: and when the ship heels, its action to the starboard side will be $V' . \sin h$: and the whole disturbing force towards the starboard side will, therefore, be $\sin h\,(V' - I \sin \delta . R)$, which by proper determination of the magnet's distance (since V' may be increased or diminished in almost any proportion) may be made $= 0$. If R or the remaining part of R is negative, the marked end of the magnet must be upwards. In consequence of the multiplication of one of the terms by $\sin \delta$, the correction thus made will be good for only one magnetic latitude.

The proportion which the term $\sin h . I \sin \delta . R$ bears to the directive force or $I \cos \delta$, being expressed by the fraction $\sin h . \tan \delta . R$, it is evident that this term, in high magnetic latitudes, may become important. I would, therefore, recommend that, when opportunity serves, an attempt should be made to determine the position of a magnet which will neutralize R. This can be done, so far as I see, only by trial with the ship's masts considerably inclined. Such an operation would probably be too troublesome in icy seas: but it might be possible to make the necessary observations in England, and then (by trial of the powers of the magnet at different distances) to define the relation between the distance of the magnet and the dip of the dipping needle, so that, knowing the dip, the magnet could be placed at once in the position in which it will neutralize R. A graduated slider to carry the magnet would make the practical use of this method very simple.

Section IV.—*Combination of Induced Magnetism with Permanent Magnetism.*

It is supposed in the following investigations that the existence of permanent magnetism produces no modification in the induced magnetism, their effects being simply combined by algebraical addition.

Whatever be the number or direction of the magnets entering into the composition of the ship, their effects on the compass may be represented by three forces: namely, one directed to the ship's head, one directed to the starboard side, and one vertically downwards. We will designate these by the letters H, S, and V, respectively.

The resolved parts of the two horizontal forces in the north and east directions are respectively $H \cos A - S \sin A$, and $H \sin A + S \cos A$. If we combine these with the expressions found for the disturbance produced in the same directions by induced magnetism, we obtain expressions which are rather long and troublesome to use. It will be better to use the expressions for the disturbing forces directed to the head and to the starboard side. We have then

Whole disturbing force towards the ship's head

$$= H + I\cos\delta . (-M + P) . \cos A + I\sin\delta . N.$$

Whole disturbing force towards the starboard side

$$= S + I\cos\delta . (M + P) . \sin A.$$

We shall now point out the way in which the numerical values of these quantities may be found from experiment.

A needle, delicately suspended, being made to vibrate horizontally, and the time occupied by a certain number of vibrations being noted, in a place on shore free from local disturbance, and also in the place of the ship's compass in any position of the ship's head, the ratio of the whole intensity of the horizontal force in the place of the ship's compass to the intensity on shore ($I\cos\delta$) is known, being the inverse ratio of the squares of the times of vibration. This force, however, is not directed to the north, but is in the disturbed direction of the needle of the ship's compass. The amount of the needle's angular disturbance towards the east being found by observation, the intensity just found must be multiplied by the cosine of the angular disturbance to give the resolved part of the force directed to the north, and by the sine of the angular disturbance to give the resolved part of the force directed to the east. The former of these, diminished by the intensity on shore, gives the actual disturbing force to the north: the latter, unaltered, gives the actual disturbing force to the east. The disturbing forces to the head and to the starboard side may now be calculated numerically, by giving numerical values to every part of these formulæ:

Disturbing force to head

= cos A × disturbing force to north + sin A × disturbing force to east.

Disturbing force to starboard side

= cos A × disturbing force to east − sin A × disturbing force to north.

These calculations are to be made for every position of the ship in which the vibraions have been observed. When A = 0°, 90°, 180°, 270°, the factors are 0 or 1: when A = 45°, 135°, 225°, 315°, the factors are equal in magnitude: in other positions of the ship, the numerical expressions for the factors are not so simple.

The calculations being performed, we have now two series of numbers corresponding to a series of different values of A; the numbers of one series are to represent (errors of observation excepted) different values of

$$\left(\frac{H}{I\cos\delta} + \tan\delta . N\right) + (-M + P)\cos A,$$

and the numbers of the other series are to represent different values of

$$\frac{S}{I\cos\delta} + (M + P)\sin A$$

and from these conditions the several constants

$$\left(\frac{H}{I\cos\delta} + \tan\delta . N\right), \qquad (-M + P), \qquad \frac{S}{I\cos\delta}, \qquad \text{and } (M + P)$$

are to be determined. This may be done by any of the methods used in astronomical or physical inquiries for determining the numerical values of the constants in a given formula which will best satisfy a number of equations of condition. The values of the constants, so found, being substituted in each equation, the agreement of the result with the number deduced from observation, within the limits of errors of observation, may be considered as a general proof of the correctness of the theory and of the accuracy of the numerical operation.

One of the constants thus found is $\frac{H}{I \cos \delta} + \tan \delta \,.\, N$. We have no means of determining separately the parts of which it consists, by observations made at one place. In a wood-built ship, where the various irons are laid in all possible positions, and where a great proportion consists of cast-iron (which does not appear usually to possess permanent magnetism) it is probable that the term $\frac{H}{I \cos \delta}$ is insignificant. In an iron-built ship we can conjecture the value of N from the values found for M and P: it will appear probable, from the subsequent investigations, that N is small, while $\frac{H}{I \cos \delta}$ may be very large.

From the values of $(-M + P)$ and $(M + P)$, the values of M and P will be immediately obtained.

We will now proceed with the consideration of the means of correcting the compass, so that its needle shall always point truly north. A due consideration of the preceding theory will show that this may be effected by a magnet or combination of magnets, and by a mass of iron, at the same level as the compass, placed on the starboard or larboard side if P is positive, or on the fore or aft side if P is negative.

Let H' be the force of the correcting magnets directed towards the head; S' the force directed to the starboard side; A' the azimuth of the mass of iron; P' the coefficient for this mass corresponding to P for the ship; M' and N' will be $= 0$. The forces produced by the mass of iron will be

Towards the north . . . . $I \cos \delta \,.\, P' \,.\, \cos 2\,A'$.
Towards the east . . . . $I \cos \delta \,.\, P' \,.\, \sin 2\,A'$.

From which the following are obtained:

Force towards the head . . . $= I \cos \delta \,.\, P' \,.\, \cos (2\,A' - A)$.
Force towards the starboard side $= I \cos \delta \,.\, P' \,.\, \sin (2\,A' - A)$.

And if the mass be on the starboard or larboard side of the compass, $A' = A \pm 90°$, and the expressions become

Force towards the head . . . $= - I \,.\, \cos \delta \,.\, P' \,.\, \cos A$.
Force towards the starboard side $= - I \,.\, \cos \delta \,.\, P' \,.\, \sin A$.

Combining these forces and those produced by the correcting magnets with the forces produced by the induced and permanent magnetism of the ship, we have the following:

Disturbing force towards the ship's head

$$= (H + I \sin\delta . N + H') + I \cos\delta (- M + P - P') \cos A.$$

Disturbing force towards the starboard side

$$= (S + S') + I \cos\delta (M + P - P') \sin A.$$

The constant terms will be destroyed by making $H' = - (H + I \sin\delta . N)$, or $\frac{H'}{I \cos\delta} = - \left(\frac{H}{I \cos\delta} + \tan\delta . N\right)$ and $\frac{S'}{I \cos\delta} = - \frac{S}{I \cos\delta}$; which determine (in terms of quantities found from the experiments) the ratios which the directive forces of the magnet or magnets introduced are to bear to the terrestrial directive force. If N have a sensible value, the value of H' here found is strictly correct for one magnetic latitude only. The distance at which a given magnet must be placed will be determined on shore by placing it transverse to the meridian, and determining by trial the distance from a compass at which it makes the tangent of the deviation equal to the ratio required.

In the variable terms, the utmost that we can do is to make $P - P' = 0$, or $P' = P$. The easiest way of determining the distance of the mass of iron which shall produce this effect is by experiment on the angular deviation which it will produce. For the effect depending on P only produces a force towards the east $= I \cos\delta . P . \sin 2 A$: the terrestrial directive force is $I \cos\delta$; therefore the deviation (supposed small,) of a compass otherwise undisturbed, is, in terms of radius, $P . \sin 2 A$; or, in degrees, $57^\circ{\cdot}3 \times P . \sin 2 A$. If $A = 45^\circ$, this is $57^\circ{\cdot}3 \times P$. But P is known from the experiments. Hence we have this rule. Having a compass on shore, place the mass of iron, which is to be mounted for corrector, at the level of the compass, and in azimuth 45°; find by trial the distance at which it will cause the compass to deviate through $57^\circ{\cdot}3 \times P$; that is the distance from the ship's compass at which it must be mounted on the starboard or larboard side.

There still remain uncorrected the following forces:

Towards the ship's head	$- I \cos\delta . M . \cos A.$
Towards the starboard side	$I \cos\delta . M . \sin A.$

From these we obtain,

Remaining disturbing force towards the north	$- I \cos\delta . M.$
Remaining disturbing force towards the east	0.

The direction of the needle, therefore, is not disturbed; these terms express only the diminution of the terrestrial directive force of which we have already spoken.

If it be desired to correct the compass accurately for all magnetic latitudes, the following is the course which must be pursued.

1. From experiments similar to those already described, determine in two different magnetic latitudes the numerical values of

$$\frac{H}{I \cos\delta} + \tan\delta . N, \text{ and } \frac{H}{I' \cos\delta'} + \tan\delta' . N:$$

and from these find H and N.

2. From experiments on a compass on shore, with a mass of iron not in the same level, and in azimuth 90°, determine a position in which it will produce the deviation $57^{\circ}\cdot 3 \times \tan \delta \,.\, N$. This is a position in which it is to be fixed in the ship; on the aft side of the compass if N is positive, or the fore side if N is negative.

3. With the mass of iron at that position, try the deviations which it produces on a compass on shore in azimuth 45° and 135°, and take half the algebraical excess of the former above the latter. This is to be added to the angle $57^{\circ}\cdot 3 \times P$, to produce the angle which the other mass on the starboard or larboard side is to correct.

4. The magnet introduced as corrector must have an intensity H' equal to $-H$.

It may be proper now to say a few words relative to the application of our theory to the observations of the dipping-needle, as made on the deck of the Rainbow.

The resolved part of the terrestrial force parallel to the ship's keel is $I \cos \delta \,.\, \cos A$, and the resolved part vertically downwards is $I \sin \delta$. Combining these with the forces in those directions produced by the permanent and induced magnetism in the ship, we have

$$\text{Cotangent of dip towards ship's head} = \frac{\text{Force towards ship's head}}{\text{Force vertically downwards}}.$$

$$= \frac{I \cos \delta \,.\, \cos A + H + I \sin \delta \,.\, N + I \cos \delta \,.\, (-M + P) \cos A}{I \sin \delta + V - I \sin \delta \,.\, Q + I \cos \delta \,.\, N \,.\, \cos A}$$

$$= \frac{\cot \delta \,(1 - M + P) \cos A + \cot \delta \left(\frac{H}{I \cos \delta} + \tan \delta \,.\, N\right)}{1 + \frac{V}{I \sin \delta} - Q + \cot \delta \,.\, N \,.\, \cos A}.$$

Let c be the observed cotangent of the dip towards the ship's head; the equation then gives

$$\cot \delta \,(1 - M + P) \cos A + \cot \delta \left(\frac{H}{I \cos \delta} + \tan \delta \,.\, N\right) = c \left(1 + \frac{V}{I \sin \delta} - Q\right)$$
$$+ c \,.\, \cot \delta \,.\, N \cos A.$$

Substituting in this the values of $(-M + P)$ and $\left(\frac{H}{I \cos \delta} + \tan \delta \,.\, N\right)$ found from the observations of intensity, we shall be able to ascertain the values of $1 + \frac{V}{I \sin \delta} - Q$ and N. Where the dipping-needle is incorrect, the best value of δ will be the incorrect dip as shown by the needle.

In like manner we find

$$\text{Cotangent of dip towards starboard side} = \frac{- I \cos \delta \,.\, \sin A + S + I \cos \delta \,.\, (M + P) \sin A}{I \sin \delta + V - I \sin \delta \,.\, Q + I \cos \delta \,.\, N \,.\, \cos A}$$

$$= \frac{- \cot \delta \,.\, (1 - M - P) \,.\, \sin A + \cot \delta \,.\, \frac{S}{I \cos \delta}}{1 + \frac{V}{I \sin \delta} - Q + \cot \delta \,.\, N \,.\, \cos A}.$$

Let c' be the observed cotangent of the dip towards the starboard side; the equation then gives

$$-\cot\delta(1-M-P).\sin A+\cot\delta.\frac{S}{I\cos\delta}=c'\left(1+\frac{V}{I\sin\delta}-Q\right)+c'.\cot\delta.N.\cos A,$$

which will assist, in the same manner as the last, to give values of $1+\frac{V}{I\sin\delta}-Q$ and N.

With regard to the effect of the ship's heeling, the following investigation appears sufficient. Supposing a magnet to be introduced, parallel to the masts, and with its marked end downwards, its effect downwards and parallel to the masts will be represented by $-V'$. Combining this with the force V of the ship in the same direction, and supposing the angle of heel to starboard to be h, we have for the force to starboard in a horizontal plane

$$\sin h\,(V'-V).$$

Combining these with the forces found in Section III, we have

Force towards ship's head, depending on the heeling,

$$\sin h\,.\,I\cos\delta\,.\,N\,.\,\sin A.$$

Force towards starboard side, depending on the heeling,

$$\sin h\,(V'-V-I\cos\delta\,.\,N\,.\,\cos A-I\sin\delta\,.\,R).$$

As we cannot ensure the neutralization of the term N by the induced magnetism of another mass of iron, (except by experiments in different magnetic latitudes) we must suppose it to exist uncorrected. It is probable that the effect of the forces depending on it will not be great. Their proportion to the directive force will be

$\sin h\,.\,N\,.\,\sin A$ for the force to the head,

and $-\sin h\,.\,N\,.\,\cos A$ for the force to the starboard side; or

$$-\sin h\,.\,N\,.\,\cos 2A$$

for the force to the magnetic east. This proportion does not increase in the high magnetic latitudes.

The proportion of the remaining force $\sin h\,(V'-V-I\sin\delta\,.\,R)$ to the directive force, which is expressed by $\sin h\left(\frac{V'-V}{I\cos\delta}-\tan\delta\,.\,R\right)$, becomes great in the high magnetic latitudes, and this force therefore ought not to be neglected. From the observations with the dipping-needle, as mentioned above, we may probably obtain the value of V, or rather $V-I\sin\delta\,.\,Q$, and may, therefore, determine V' so as partially to neutralize it. Still the term $\tan\delta\,.\,R$ remains: and therefore the correction would be imperfect. It would probably be best, therefore, to attempt the correction tentatively (as mentioned before, for wood-built ships). The vessel being placed with her head to the north, and made to heel through the angle h, and the place of a given

magnet (arranged as before mentioned) being determined so as to correct any new deviation depending on the heeling, V' will $= V + I \cos \delta . N + I \sin \delta . R$. As we cannot easily separate the different terms of this expression, there appears no way of providing for the correction in different magnetic latitudes but by trial in each.

If V should have a sensible magnitude, the principal part of the error of the compass at any place of the ship, when the ship is heeling, will depend on V. If it appears from other of the investigations, that V is small, we may be assured that the deviation depending upon the ship's heeling will not, except in high latitudes, be very great.

Section V.—*Application of the Theory to the Observations made in the Rainbow.*

As the disturbance of the compass was not observed in the experiments for intensity, it has been interpolated graphically between those previously observed. From the times of vibration given in Section II. the following numbers are computed by the methods of Section IV.

No. of station.	Azimuth of ship's head.	Disturbance of compass to East.	Intensity to N. / $I \cos \delta$	Disturbing force to N. / $I \cos \delta$	Disturbing force to E. / $I \cos \delta$	Dist. force to ship's head. / $I \cos \delta$	Dist. force to starb. side / $I \cos \delta$
I.	0°	− 36° 0′	+ 0·18	− 0·82	− 0·13	− 0·82	− 0·13
	90	− 33 50	+ 1·15	+ 0·15	− 0·77	− 0·77	− 0·15
	180	+ 6 0	+ 1·83	+ 0·83	+ 0·19	− 0·83	− 0·19
	270	+ 45 30	+ 0·77	− 0·23	+ 0·79	− 0·79	− 0·23
II.	0	− 17 0	+ 0·68	− 0·32	− 0·21	− 0·32	− 0·21
	90	− 14 0	+ 1·14	+ 0·14	− 0·28	− 0·28	− 0·14
	180	+ 9 20	+ 1·34	+ 0·34	+ 0·22	− 0·34	− 0·22
	270	+ 24 0	+ 0·73	− 0·27	+ 0·32	− 0·32	− 0·27
III.	0	− 12 30	+ 0·82	− 0·18	− 0·18	− 0·18	− 0·18
	90	− 12 40	+ 1·14	+ 0·14	− 0·26	− 0·26	− 0·14
	180	+ 7 20	+ 1·32	+ 0·32	+ 0·17	− 0·32	− 0·17
	270	+ 23 0	+ 0·72	− 0·28	+ 0·31	− 0·31	− 0·28
IV.	0	− 9 45	+ 0·89	− 0·11	− 0·15	− 0·11	− 0·15
	90	− 7 10	+ 1·15	+ 0·15	− 0·14	− 0·14	− 0·15
	180	+ 8 30	+ 1·18	+ 0·18	+ 0·18	− 0·18	− 0·18
	270	+ 10 15	+ 0·66	− 0·35	+ 0·12	− 0·12	− 0·35

It is impossible to glance at the numbers in the two last columns without noticing the smallness of the variation in each of the disturbing forces, as referred to lines of the ship, while the ship was turned round. From the moment when this Table was completed, it was perfectly clear that the explanation of the principal part of the disturbances of the compass was to be sought in the permanent magnetism of the ship.

Confining ourselves for the present to Station I., we have by the formulæ of the last section,

$$\left(\frac{H}{I \cos \delta} + \tan \delta . N\right) + (-M + P) = -0·82$$

$$\left(\frac{H}{I \cos \delta} + \tan \delta . N\right) \qquad = -0·77$$

$$\left(\frac{H}{I \cos \delta} + \tan \delta . N\right) - (-M + P) = -0·83$$

$$\left(\frac{\mathrm{H}}{\mathrm{I}\cos\delta} + \tan\delta\,.\,\mathrm{N}\right) = -\,0{\cdot}79$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta} = -\,0{\cdot}13$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta} + (\mathrm{M}+\mathrm{P}) = -\,0{\cdot}15$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta} = -\,0{\cdot}19$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta} - (\mathrm{M}+\mathrm{P}) = -\,0{\cdot}23$$

The most probable values appear to be

$$\frac{\mathrm{H}}{\mathrm{I}\cos\delta} + \tan\delta\,.\,\mathrm{N} = -\,0{\cdot}80$$

$$-\,\mathrm{M}+\mathrm{P} = 0{\cdot}00$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta} = -\,0{\cdot}17$$

$$\mathrm{M}+\mathrm{P} = 0{\cdot}04$$

whence

$$\mathrm{M} = 0{\cdot}02, \qquad \mathrm{P} = 0{\cdot}02.$$

The two last quantities are so small that the experiments can hardly be supposed to give their precise values. The value of M indicates that, when the direction is corrected, the intensity will be enfeebled $\frac{1}{50}$ part: that of P shows that, supposing the direction corrected by magnets only, there will be a deviation of the compass changing sign at the alternate quadrants, whose maximum is little more than 1°, and which is such that the needle turns to the right, or observed azimuths appear too small, when the azimuth of the ship's head is between 0 and 90°.

To prove these results completely, the following calculations were made. The two permanent magnetic forces represented by $-\,0{\cdot}80$ parallel to the ship's keel, and $-\,0{\cdot}17$ transverse to it, may be compounded into one force $-\,0{\cdot}82$, making an angle α with the ship's keel, where $\tan\alpha = \frac{17}{80}$ (the horizontal part of terrestrial magnetism being represented by 1·00). A line being taken to represent 1·00, with one end of this line for centre and with radius 0·82, a circle was described; upon this circle the angle α was graphically determined, and the different angles $\mathrm{A} + \alpha$ were laid down (A being the azimuth of the ship's head) for every observation from No. 1. to 34. Each of the points on the circle thus determined was joined with the other end of the line, whose length = 1·00. It is clear that, if the force acting on the north end of the compass be the force compounded of terrestrial magnetism invariable in direction and magnitude, and of ship's magnetism invariable in magnitude, but changing direction with the ship, the resulting actual force will be represented by the joining

line last drawn. The angles made by that joining line with the line 1·00 ought, therefore, to be the same as the observed disturbance of compass, or if there is any certain difference, that difference ought to be explainable by the term P mentioned above. The following table contains the values of the angles made by the joining line with the line 1·00 (as taken from the graphical construction), or theoretical disturbance of the compass, compared with the observed disturbance; the sign + denotes that the needle is turned to the left.

No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.	No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.
	° ′	° ′	° ′	° ′		° ′	° ′	° ′	° ′
1	203 5	−16 50	−15 50	−1 0	19	1 35	+40 45	+43 0	−2 15
2	214 53	−22 45	−21 0	−1 45	20	19 25	+51 20	+55 0	−3 40
3	220 0	−23 20	−23 25	+0 5	21	38 25	+50 50	+52 40	−1 50
4	230 0	−30 5	−27 40	−2 25	22	57 45	+46 30	+47 5	−0 35
5	240 50	−34 5	−32 20	−1 45	23	76 55	+39 15	+39 50	−0 35
6	248 50	−36 40	−35 35	−1 5	24	93 10	+33 5	+33 5	0 0
8	256 4	−40 2	−38 30	−1 32	25	109 0	+26 40	+26 15	+0 25
9	267 44	−44 27	−43 15	−1 12	26	125 50	+19 40	+19 0	+0 40
10	276 12	−47 50	−46 30	−1 20	27	142 10	+11 55	+11 50	+0 5
11	282 57	−49 27	−48 35	−0 52	28	159 10	+ 4 20	+ 4 0	+0 20
12	292 17	−52 25	−51 25	−1 0	29	171 5	− 1 35	− 1 20	−0 15
13	294 0	−53 45	−51 50	−1 55	30	189 45	−11 0	− 9 55	−1 5
14	300 35	−54 50	−53 40	−1 10	31	202 5	−16 45	−15 25	−1 20
15	308 0	−53 50	−54 40	+0 50	32	220 25	−25 10	−23 40	−1 30
16	313 47	−54 2	−54 50	+0 48	33	248 55	−37 50	−35 40	−2 10
17	321 40	−50 10	−53 40	+3 30	34	278 15	−48 25	−47 10	−1 15
18	338 25	−33 0	−35 30	+2 30					

It is quite evident from this table, first, that almost the whole disturbance of the compass is accounted for by the permanent magnetism; secondly, that the residual part follows with sufficient approximation the law of changing signs at the successive quadrants (modified in a small degree by the disturbance in the needle's direction), and with a maximum value not much different from the value 1° already predicted from the observations of intensity. In the quadrants adjacent to the azimuth 0° the maximum appears greater than this quantity, as it ought to appear, in consequence of the great diminution in the needle's directive power.

There remained only, for the complete verification of the theory, to effect an actual correction of the compass. With a two-feet bar magnet placed transversely to the magnetic meridian, experiments were made at Greenwich for ascertaining the distance at which it must be placed below a compass in order to make the needle deviate through 39° 25′ (the angle whose natural tangent = 0·82, the proportion of the ship's permanent magnetic force to the terrestrial directive force at Deptford). The magnet*

* I know not whether the following observation possesses any novelty or interest. A pair of 2-feet bar magnets had been constructed for me a year or more before this time by Messrs. Watkins and Hill. On trial, one was found to have not more than half the intensity of the other: it was retouched by the makers: it was again found to be feeble, was again touched; and had been laid up with its fellow and with the keepers on for some months. When trials were made for ascertaining the distance at which the magnets intended for

was then placed in a groove, cut in a board, and making with the edge of the board the angle whose tangent $= \frac{17}{80}$. This mode of mounting was adopted for facility of fixing in the ship, as it was then necessary only to make the edge of the board parallel to the ship's keel, the magnet being at the proper distance below the compass. A roll of iron plate was also prepared, tolerably free from permanent magnetism, and experiments were made to ascertain the distance from a compass at which in azimuth 45° it would cause a deviation something greater than 1°; and arrangements were made for fixing this roll on one side of the ship's compass, in the direction nearly transverse to the keel, and at the same height as the compass card.

The magnet being placed in the proper position and at the assigned distance below the compass, and the roll of iron plate being mounted, on making observations in the usual way, it was found (without waiting for the complete calculations) that the deviation was over-corrected. Whether any error had occurred in the measures, or whether the inductive action of the ship increased the power of the magnet (which was placed with its poles in the direction opposite to those of the ship) I do not know. The distance of the magnet was increased, its direction being carefully preserved, and then a series of observations was made and reduced in the usual manner. The results are contained in the following table.

No. of observation.	True azimuth of ship's head.	Disturbance of compass.	No. of observation.	True azimuth of ship's head.	Disturbance of compass.
171	152° 6′	+0° 54′	177	334° 22′	−1° 22′
172	176 56	+0 34	178	357 34	−0 4
173	210 56	−0 41	179	26 34	−0 14
174	239 51	+0 9	180	56 6	+1 54
175	269 53	−0 8	181	87 51	+1 9
176	300 36	−0 6	182	118 36	+0 24

The correction may be considered as perfect as it is possible to make from observations of no greater delicacy than those on which the position of the correctors was determined. I think it is evident that the true maximum error does not exceed half a degree.

Proceeding in the same manner with Station II., we find the following equations.

$$\left(\frac{H}{I\cos\delta} + \tan\delta . N\right) + (-M + P) = -0{\cdot}32$$

$$\left(\frac{H}{I\cos\delta} + \tan\delta . N\right) \qquad = -0{\cdot}28$$

correcting the ship's compass should be placed, the keepers were taken off, and the intensity of this magnet was found fully equal to that of its fellow. It was left during one night standing vertically with its marked end upwards: the next morning it had lost two-thirds of its power. I have since examined the powers of several pairs of magnets shortly after taking off their keepers and after the lapse of two or three days, and in every instance one magnet of each pair has lost much of its power.

$$\left(\frac{H}{I\cos\delta} + \tan\delta . N\right) - (-M + P) = -0{\cdot}34$$

$$\left(\frac{H}{I\cos\delta} + \tan\delta . N\right) = -0{\cdot}32$$

$$\frac{S}{I\cos\delta} = -0{\cdot}21$$

$$\frac{S}{I\cos\delta} + (M + P) = -0{\cdot}14$$

$$\frac{S}{I\cos\delta} = -0{\cdot}22$$

$$\frac{S}{I\cos\delta} - (M + P) = -0{\cdot}27$$

The most probable values appear to be

$$\frac{H}{I\cos\delta} + \tan\delta . N = -0{\cdot}32$$

$$-M + P = +0{\cdot}01$$

$$\frac{S}{I\cos\delta} = -0{\cdot}21$$

$$M + P = +0{\cdot}065$$

whence $M = 0{\cdot}03$, $P = 0{\cdot}04$. The last term denotes that the disturbance not depending on permanent magnetism would amount at its maximum to $2°\frac{1}{4}$, changing signs in successive quadrants, and being negative (in its effects on apparent azimuth) when the azimuth of the ship's head is between 0 and 90°. The large terms show that the permanent magnetism (as compared with the terrestrial force) may be represented by 0·38, inclined to the direction of the keel by an angle α where $\tan\alpha = \frac{21}{32}$. Computing as for Station I., we get the following table of comparisons.

No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.	No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.
	° ′	° ′	° ′	° ′		° ′	° ′	° ′	° ′
35	282 51	−21 36	−20 5	−1 31	45	103 36	+12 54	+11 50	+1 4
36	300 4	−12 41	−14 50	+2 9	46	124 26	+ 7 26	+ 6 10	+1 16
37	320 49	− 1 19	− 3 55	+2 36	47	143 57	+ 1 26	+ 1 0	+0 26
38	340 7	+ 9 31	+ 8 5	+1 26	48	163 16	− 4 16	− 4 30	+0 14
39	353 48	+15 4	+15 5	−0 1	49	179 6	− 9 6	− 8 50	−0 16
40	11 26	+18 34	+20 30	−1 56	50	203 1	−16 16	−14 45	−1 31
41	31 14	+19 46	+22 35	−2 49	51	222 21	−21 51	−18 55	−2 56
42	49 47	+19 51	+21 50	−1 59	52	244 56	−26 26	−22 5	−4 21
43	67 3	+18 12	+19 35	−1 23	53	267 46	−24 16	−22 30	−1 46
44	85 1	+14 59	+16 15	−1 16					

The residual term here follows with great accuracy the law of the deviation depending on P, and its magnitude is, as nearly as the nature of the observation allows, the same as that predicted.

For Station III.

$$\left(\frac{H}{I\cos\delta} + \tan\delta \, . \, N\right) + (-M + P) = -0{\cdot}18$$

$$\left(\frac{H}{I\cos\delta} + \tan\delta \, . \, N\right) = -0{\cdot}26$$

$$\left(\frac{H}{I\cos\delta} + \tan\delta \, . \, N\right) - (-M + P) = -0{\cdot}32$$

$$\left(\frac{H}{I\cos\delta} + \tan\delta \, . \, N\right) = -0{\cdot}31$$

$$\frac{S}{I\cos\delta} = -0{\cdot}18$$

$$\frac{S}{I\cos\delta} + (M + P) = -0{\cdot}14$$

$$\frac{S}{I\cos\delta} = -0{\cdot}17$$

$$\frac{S}{I\cos\delta} - (M + P) = -0{\cdot}28$$

The most probable values are

$$\frac{H}{I\cos\delta} + \tan\delta \, . \, N = -0{\cdot}27$$

$$-M + P = +0{\cdot}07$$

$$\frac{S}{I\cos\delta} = -0{\cdot}19$$

whence

$$M + P = +0{\cdot}07$$

$$M = 0{\cdot}00, \qquad P = 0{\cdot}07.$$

The term of the disturbance of the compass which changes sign in the alternate quadrant ought therefore to have a maximum value of 4°; its sign, in each quadrant, ought to be the same as at Station I. and II. The permanent magnetism of the ship is represented by 0·33, inclined to the ship's keel at an angle whose natural tangent is $\frac{19}{27}$. On computing the effect of this independent magnetism, in the same manner as for Station I., the following Table is formed.

No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.	No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.
54	284° 11′	−19° 41′	−16° 10′	−3° 31′	64	93° 11′	+11° 49′	+12° 30′	−0° 41′
55	300 24	−13 24	−11 30	−1 54	65	120 36	+ 7 54	+ 6 10	+1 44
56	311 18	− 4 18	− 6 45	+2 27	66	139 46	+ 3 44	+ 1 35	+2 9
57	324 26	+ 2 49	− 0 35	+3 24	67	163 9	− 3 9	− 4 30	+1 21
58	340 51	+ 7 39	+ 7 30	+0 9	68	187 9	−10 39	− 9 55	−0 44
59	2 34	+11 56	+15 15	−3 19	69	216 6	−18 21	−15 50	−2 31
60	22 16	+14 29	+18 40	−4 11	70	235 11	−21 41	−18 20	−3 21
61	38 11	+16 19	+19 25	−3 6	71	259 59	−24 29	−19 20	−5 9
62	60 34	+15 26	+17 55	−2 29	72	275 41	−21 41	−17 40	−4 1
63	81 36	+13 24	+14 40	−1 16					

Remarking that the residual errors with the sign $-$ exceed in magnitude and number those with the sign $+$, I conjecture that the index error has been erroneously determined, to the extent perhaps of $40'$ or $50'$. With this supposition, the agreement of the observed residual term with the theoretical residual term is very close.

For Station IV. we have as follows:

$$\left(\frac{\mathrm{H}}{\mathrm{I}\cos\delta}+\tan\delta\,.\,\mathrm{N}\right)+(-\mathrm{M}+\mathrm{P})=-0{\cdot}11$$

$$\left(\frac{\mathrm{H}}{\mathrm{I}\cos\delta}+\tan\delta\,.\,\mathrm{N}\right)=-0{\cdot}14$$

$$\left(\frac{\mathrm{H}}{\mathrm{I}\cos\delta}+\tan\delta\,.\,\mathrm{N}\right)-(-\mathrm{M}+\mathrm{P})=-0{\cdot}18$$

$$\left(\frac{\mathrm{H}}{\mathrm{I}\cos\delta}+\tan\delta\,.\,\mathrm{N}\right)=-0{\cdot}12$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta}=-0{\cdot}15$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta}+(\mathrm{M}+\mathrm{P})=-0{\cdot}15$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta}=-0{\cdot}18$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta}-(\mathrm{M}+\mathrm{P})=-0{\cdot}35$$

The most probable values appear to be

$$\frac{\mathrm{H}}{\mathrm{I}\cos\delta}+\tan\delta\,.\,\mathrm{N}=-0{\cdot}14$$

$$-\mathrm{M}+\mathrm{P}=+0{\cdot}035$$

$$\frac{\mathrm{S}}{\mathrm{I}\cos\delta}=-0{\cdot}21$$

$$\mathrm{M}+\mathrm{P}=+0{\cdot}10$$

whence $\mathrm{M}=0{\cdot}03,\quad \mathrm{P}=0{\cdot}07.$

The coefficient therefore of the term which changes signs at alternate quadrants ought to be 4° nearly; the permanent magnetism ought to be represented by $0{\cdot}25$ inclined at an angle whose tangent $=\frac{21}{14}$. The following Table will show the comparison of the term computed (as before) from the permanent magnetism with the disturbance observed.

No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.	No. of observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.
	° ′	° ′	° ′	° ′		° ′	° ′	° ′	° ′
73	96 21	− 9 21	− 8 20	−1 1	83	310 6	+ 3 54	− 1 30	+5 24
74	111 6	− 2 6	− 4 5	+1 59	84	326 46	− 0 46	− 4 50	+4 4
76	150 36	+ 8 54	+ 8 35	+0 19	85	350 16	− 6 16	− 9 10	+2 54
77	167 6	+ 8 54	+12 15	−3 21	86	18 1	−12 31	−13 0	+0 29
78	183 41	+ 9 49	+14 20	−4 31	87	39 36	−15 21	−14 45	−0 36
79	196 46	+10 14	+14 40	−4 26	88	65 9	−15 39	−14 0	−1 39
80	229 54	+ 7 36	+12 50	−5 14	89	84 34	−12 4	−11 0	−1 4
81	246 59	+ 8 1	+10 20	−2 19					
82	275 6	+ 7 9	+ 5 50	+1 19					

The agreement of the residual term here with the theoretical residual term is not so perfect as at the other stations, but is nevertheless very close. A trifling alteration in the independent magnetism would make the agreement perfect. I may observe that, *à priori*, the existence of a disagreement at this station is probable. The observations of intensity and of disturbance of the compass were not made at the same time; and it is extremely probable that the box of chain-cable (mounted on wheels upon the deck, at no great distance from Station IV.) had been moved in the intermediate time.

Attempts were made to correct the compass at Stations II., III., and IV., in the same manner as at Station I. They did not, however, succeed so perfectly. I attribute this failure to the following cause. As the observations at Station I. had seemed to show that a small tentative adjustment might be necessary, a tentative adjustment was tried, depending of course upon the indications of the compass, at each of the other stations before making a round of observations. The compass it was found had become exceedingly sluggish (probably from the blunting of the suspending point by very frequent movements), two readings for the same bearing being sometimes obtained differing 8° or more. By one of these errors an adjustment might be affected, and its consequence would be found in every observation made while the magnets were in the position so adjusted. As a general rule it is to be recommended that no tentative adjustment be made, except the whole apparatus is in the highest possible order. When the vessel was prepared for sea, three compasses (at Stations I. II. and III.) were fitted with magnets and masses of soft iron placed according to the directions in the preceding section, and arranged, as to intensity and position of the magnets, and as to maximum effect of the soft iron, in accordance with the numbers just found; and the direction of these three compasses has appeared to be, as far as general observation could discover, quite correct. The compass at Station II. occasionally differed from the others two or three degrees; but this error might be occasioned by a blow which the magnet received, or might be produced by the effect of the powerful 2-feet magnet under Station I. The magnets under Stations II. and III. were 14-inch magnets, producing no sensible effect at any station but those to which they belonged.

On the whole, I conclude that the explanation of the deviations of the compass, by the combined powers of independent magnetism of the ship and induced magnetism produced by terrestrial action, is perfect; and that there is no reason to doubt that by the introduction of antagonist magnets and masses of soft iron the correction may be made perfect.

I shall now proceed with the discussion of the observations made with the dipping-needle.

The equation depending on the dip towards the ship's head given in the last section, being applied to Station I., and the substitution of 0·00 for $-M+P$, 0·80 for $\frac{H}{I\cos\delta}+\tan\delta\,.\,N$, and 72° 40′ for δ, being made, the equation assumes the following form:

$$0{\cdot}312\,.\cos A - 0{\cdot}250 = c\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}312\,.\,c\,.\,N\,.\cos A.$$

Substituting in each of the observations from No. 35 to 53, for Station I., we have the following equations.

No. of observation.	Equation.
35	$-0{\cdot}181 = -0{\cdot}197\left(1+\frac{V}{I\sin\delta}-Q\right) - {\cdot}014\,N.$
37	$-0{\cdot}008 = -0{\cdot}047$ .... $-{\cdot}011$ ..
38	$+0{\cdot}043 = +0{\cdot}010$ .... $+{\cdot}003$ ..
39	$+0{\cdot}060 = +0{\cdot}032$ .... $+{\cdot}010$ ..
40	$+0{\cdot}056 = +0{\cdot}033$ .... $+{\cdot}010$ ..
41	$+0{\cdot}017 = -0{\cdot}015$ .... $-{\cdot}004$ ..
42	$-0{\cdot}048 = -0{\cdot}067$ .... $-{\cdot}013$ ..
43	$-0{\cdot}128 = -0{\cdot}132$ .... $-{\cdot}016$ ..
44	$-0{\cdot}223 = -0{\cdot}206$ .... $-{\cdot}005$ ..
45	$-0{\cdot}323 = -0{\cdot}320$ .... $+{\cdot}023$ ..
46	$-0{\cdot}427 = -0{\cdot}404$ .... $+{\cdot}071$ ..
47	$-0{\cdot}502 = -0{\cdot}468$ .... $+{\cdot}118$ ..
48	$-0{\cdot}548 = -0{\cdot}535$ .... $+{\cdot}160$ ..
49	$-0{\cdot}562 = -0{\cdot}552$ .... $+{\cdot}172$ ..
50	$-0{\cdot}537 = -0{\cdot}535$ .... $+{\cdot}153$ ..
51	$-0{\cdot}480 = -0{\cdot}473$ .... $+{\cdot}109$ ..
52	$-0{\cdot}382 = -0{\cdot}392$ .... $+{\cdot}052$ ..
53	$-0{\cdot}262 = -0{\cdot}285$ .... $+{\cdot}003$ ..

The sum of the equations from 35 to 44, and from 45 to 53, give respectively,

$$-0{\cdot}412 = -0{\cdot}589\left(1+\frac{V}{I\sin\delta}-Q\right)-0{\cdot}030\,.\,N.$$

$$-4{\cdot}023 = -3{\cdot}964\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}861\,.\,N.$$

When the rudeness of the observations is considered, it will be evident that the first of these equations is wholly unfit (from the smallness of its coefficients) to be combined with the latter for the determination of two unknown quantities. If we add them together we find

$$-4{\cdot}435 = -4{\cdot}553\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}831\,.\,N$$

and if we assume N to be small (which assumption appears, from the nature of the integral on which it depends, to be well founded), we must infer that the vertical part of the ship's permanent magnetism is very small.

The equation for the transversal dip, substituting 0·04 for M + P and − 0·17 for $\frac{S}{I \cos \delta}$, becomes

$$-0·300 \,.\, \sin A - 0·053 = c' \left(1 + \frac{V}{I \sin \delta} - Q\right) + 0·312 \,.\, c' \,.\, N \,.\, \cos A.$$

Substituting in each of the observations from 54 to 72, we get the following equations.

No. of observation.	Equation.
54	$+ ·238 = + ·203 \left(1 + \frac{V}{I \sin \delta} - Q\right) + ·015$ N.
55	+ ·217 = + ·190 .... + ·024 ..
56	+ ·172 = + ·114 .... + ·024 ..
57	+ ·121 = + ·079 .... + ·020 ..
58	+ ·045 = + ·016 .... + ·005 ..
59	− ·068 = − ·070 .... − ·022 ..
60	− ·167 = − ·176 .... − ·051 ..
61	− ·238 = − ·245 .... − ·060 ..
62	− ·314 = − ·312 .... − ·048 ..
63	− ·350 = − ·381 .... − ·017 ..
64	− ·352 = − ·344 .... + ·006 ..
65	− ·311 = − ·315 .... + ·050 ..
66	− ·247 = − ·249 .... + ·059 ..
67	− ·140 = − ·196 .... + ·058 ..
68	− ·016 = − ·041 .... + ·013 ..
69	+ ·126 = + ·087 .... − ·022 ..
70	+ ·193 = + ·148 .... − ·026 ..
71	+ ·243 = + ·196 .... − ·011 ..
72	+ ·246 = + ·203 .... − ·006 ..

The sum of the equations from 54 to 58 gives

$$(1) + ·793 = + ·602 \left(1 + \frac{V}{I \sin \delta} - Q\right) + ·088 \,.\, N.$$

The sum of the equations from 59 to 63 gives

$$(2) - 1·137 = - 1·184 \left(1 + \frac{V}{I \sin \delta} - Q\right) - ·198 \,.\, N.$$

The sum of the equations from 64 to 68 gives

$$(3) - 1·066 = - 1·145 \left(1 + \frac{V}{I \sin \delta} - Q\right) + ·186\, N.$$

The sum of the equations from 69 to 72 gives

$$(4) + ·808 = + ·634 \left(1 + \frac{V}{I \sin \delta} - Q\right) - ·065 \,.\, N.$$

(1) − (2) − (3) + (4) give

$$+ 3·804 = + 3·565 \left(1 + \frac{V}{I \sin \delta} - Q\right) + ·035\, N.$$

(1) — (2) + (3) — (4) give

$$+0{\cdot}056 = +{\cdot}007\left(1+\frac{V}{I\sin\delta}-Q\right)+{\cdot}537\,N.$$

From the two last equations, $1+\frac{V}{I\sin\delta}-Q=1{\cdot}06$, $N=+{\cdot}09$; which values, with very trifling alterations, would satisfy the equation derived from the longitudinal dips. The excess of the numbers on the first side with the sign + and the defect of those with the sign — might be caused by an erroneous determination of $\frac{S}{I\cos\delta}$, but it is far more probable that it has originated here in an error of adjustment of the dipping-needle, made while the ship was heeling: it produces no sensible effect on the solutions of the equations.

The equation for dip towards the ship's head at Station III. becomes, on substituting the numbers proper for that station,

$$0{\cdot}407\cos A - 0{\cdot}103 = c\left(1+\frac{V}{I\sin\delta}-Q\right)+c\,.\,0{\cdot}381\cos A\,.\,N.$$

Forming the separate equations, combining those from No. 35 to 43 in one group, and those from 44 to 53 in another group, we obtain

$$+1{\cdot}629 = +1{\cdot}855\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}591\,.\,N,$$

$$+3{\cdot}308 = -3{\cdot}260\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}924\,.\,N.$$

From these, $1+\frac{V}{I\sin\delta}-Q=0{\cdot}95$, $N=-0{\cdot}22$.

The equation for dip towards the starboard side at the same station is

$$-0{\cdot}354\sin A - {\cdot}072 = c'\left(1+\frac{V}{I\sin\delta}-Q\right)+c'\,.\,0{\cdot}381\cos A\,.\,N.$$

Grouping the equations from 54 to 57, 60 to 63, 64 to 68, 69 to 71, and 72, and then combining these groups so as to make all the multipliers of the unknown quantities additive, one in each equation, we get the following equations

$$+4{\cdot}357 = +4{\cdot}416\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}081\,.\,N.$$

$$+0{\cdot}485 = +0{\cdot}524\left(1+\frac{V}{I\sin\delta}-Q\right)+0{\cdot}777\,.\,N.$$

From these, $1+\frac{V}{I\sin\delta}-Q=0{\cdot}99$, $N=-0{\cdot}04$.

The agreement of these results with those obtained for the dip towards the head is as close as could be expected. The equations for determining N cannot be made very favourable, and great precision in its value is not to be hoped for. The agreement of the two values of $1+\frac{V}{I\sin\delta}-Q$ is a proof of the accuracy of the determinations of horizontal intensity, and of the general correctness of the theory which

connects the different observations. For upon the values of P, deduced from the observations of intensity, the first term in every one of these equations depends (the difference in the numerical values of the coefficients 0·407 and 0·354 depends entirely upon it): a very small alteration of P would make the results for $1+\frac{V}{I\sin\delta}-Q$ precisely equal: the omission of P would have caused very great discordance in the values of $1+\frac{V}{I\sin\delta}-Q$.

I have not been equally successful with the observations at Station IV. The dipping-needle used there was, as I have mentioned, in the proximity of large moveable masses of iron, the windlass, the anchors, and the box of chain-cable. Whatever the cause may be, the observations are in themselves discordant. Upon trying whether the cotangent of the dip could be approximately represented by $a\cos A+b$ for dips towards the head, and by $a'\sin A+b'$ for dips towards the starboard side, it was found that the discordances were between three and four times as great at Station IV. as at Station III. I have not thought it worth while to occupy space with the equations, &c. at this station; considering that the results already obtained are sufficient for my present purpose.

The quantity Q it will be remarked (from its expression in Section III.) is of the same order as M, and therefore probably small. Hence the assertion that $1+\frac{V}{I\sin\delta}-Q$ differs little from 1, enables us at once to assert that V, the permanent vertical magnetic force of the ship, is small.

Section VI.—*Observations not essential to the Theory.*

The following account of the observed disturbance of the compass on the upper floor of the stage will probably be sufficient.

At Station I. the disturbance vanished when the azimuth of the ship's head was about 150° and 320°. The greatest + disturbance (needle deviating to the left) took place in azimuth 78° nearly, and amounted to + 5°; the greatest − disturbance occurred in azimuth 260°, and amounted to − 10°.

At Station II. the disturbance vanished in azimuths 156° and 330° nearly. The greatest + disturbance was in azimuth 50° or 55°, and exceeded 10°; the greatest − disturbance was in azimuth 267°, and amounted to $11\frac{1}{2}$°.

At Station III. the disturbance vanished in azimuth 150° and 330° nearly. The greatest + disturbance was in azimuth 76°, and amounted to $7\frac{1}{4}$°; the greatest − disturbance was in azimuth 230°, and amounted to $9\frac{1}{2}$°.

At Station IV. the disturbance vanished in azimuths 155° and 320° nearly. The greatest + disturbance was in azimuth 60° nearly, and amounted to 8°; the greatest − disturbance was in azimuth 230° nearly, and amounted to about 8°.

These disturbances are evidently referable, for the greatest part of their amount,

to permanent magnetism; though the effect of induced magnetism is sensible, especially in the observations at Station I.

The observations made with the dipping-needles and large horizontal magnets on shore, were conducted under circumstances of weather so unfavourable (amidst torrents of rain and very heavy gusts of wind), that it has not appeared worth while to transcribe them. The following result, however, may be stated as deducible from them with perfect certainty. On one or two occasions there appeared to be reason to think that the ship's head, when near, attracted the upper end of the dipping-needle, or the unmarked end of the horizontal magnet, but the effect hardly exceeded the errors of observation. But in every instance when the ship's stern was brought near to the dipping-needles or magnets, it powerfully attracted the lower or marked end. The most distinct estimate of its power may be obtained from the following observation. On August 2, the ship's head being south nearly, and a dipping-needle vibrating in the meridian being placed at the distance 25 feet from the stern, the dip of the needle was increased $7^\circ\ 30'$. I may remark that the dipping-needle is an infinitely less delicate instrument (where horizontal forces only are concerned) than the large horizontal magnet, as used by Gauss, with reflector and graduated scale, suspended by one bundle of silk fibres if parallel to the magnetic meridian, or by two if transverse to it. The dipping-needle, however, is mounted with much greater speed and less trouble than the magnet, and is more easily protected from the violence of the weather.

Section VII.—*Observations of the Disturbance of the Compass in the Iron-built Sailing-ship Ironsides.*

On the 26th and 27th of October 1838, I examined the binnacle compass of the iron sailing-ship Ironsides in the Brunswick Dock, Liverpool. The observations were made by placing one azimuth compass in the position of the binnacle, and another on shore, and with each of these compasses observing a small signal carried by the other. In this manner the reductions for locality, &c. were completely avoided, but every result was liable to the errors of two compasses. The experience of the investigations in the Rainbow having shown the importance of observations of horizontal intensity, I applied the intensity apparatus in every position of the ship in which the compass was observed. The time occupied by forty vibrations of the needle on shore was $195^{s}\cdot 0$. The values for disturbing forces in the following Table are computed by the methods of Section IV.

Reference to observation.	Azimuth of ship's head.	Disturbance of compass.	Time of forty vibrations.	Intensity to N. $\frac{}{\text{I} \cos \delta}$	Dist. force to N. $\frac{}{\text{I} \cos \delta}$	Dist. force to E. $\frac{}{\text{I} \cos \delta}$	Dist. force to head. $\frac{}{\text{I} \cos \delta}$	Dist. force to starboard. $\frac{}{\text{I} \cos \delta}$
	° ′	° ′	s					
a	9 50	−28 20	262·8	0·485	−0·515	+0·261	−0·462	+0·345
b	23 0	−22 30	279·4	0·450	−0·550	+0·186	−0·433	+0·387
c	32 35	−11 20	299·2	0·416	−0·584	+0·083	−0·447	+0·385
d	47 40	+ 6 40	303·3	0·411	−0·589	−0·048	−0·432	+0·403
e	58 55	+16 50	289·4	0·435	−0·565	−0·131	−0·405	+0·416
f	78 40	+28 50	256·3	0·507	−0·493	−0·279	−0·371	+0·428
g	89 0	+35 0	228·4	0·597	−0·403	−0·418	−0·425	+0·396
h	112 0	+27 10	204·4	0·810	−0·190	−0·416	−0·314	+0·332
i	151 0	+25 30	179·8	1·062	+0·062	−0·506	−0·299	+0·413
k	171 50	+16 0	171·4	1·244	+0·244	−0·357	−0·293	+0·318
l	184 55	+10 55	166·1	1·353	+0·353	−0·261	−0·330	+0·290
m	211 30	− 0 40	163·0	1·431	+0·431	+0·017	−0·376	+0·211
n	233 30	− 6 20	163·2	1·419	+0·419	+0·157	−0·376	+0·243
o	250 35	−11 50	166·2	1·347	+0·347	+0·282	−0·381	+0·233
p	279 35	−20 20	174·4	1·172	+0·172	+0·434	−0·399	+0·242
q	304 20	−25 20	188·7	0·965	−0·035	+0·457	−0·397	+0·229
r	333 10	−30 30	209·7	0·745	−0·255	+0·439	−0·426	+0·277
s	350 50	−29 20	235·6	0·597	−0·403	+0·336	−0·452	+0·267

Expressing each of the values of $\frac{\text{Disturbing force to head}}{\text{I} \cos \delta}$ by the formula

$$\left(\frac{\text{H}}{\text{I} \cos \delta} + \tan \delta \,.\, \text{N}\right) + (\text{P} - \text{M}) \cos \text{A},$$

we get the following series of equations.

Reference to observation.	Equation.
a	$-0{\cdot}462 = \left(\frac{\text{H}}{\text{I} \cos \delta} + \tan \delta \,.\, \text{N}\right) + 0{\cdot}985\ (\text{P} - \text{M})$
b	− 0·433 = ... + 0·921........
c	− 0·447 = ... + 0·843........
d	− 0·432 = ... + 0·673........
e	− 0·405 = ... + 0·516........
f	− 0·371 = ... + 0·197........
g	− 0·425 = ... + 0·017........
h	− 0·314 = ... − 0·375........
i	− 0·299 = ... − 0·875........
k	− 0·293 = ... − 0·990........
l	− 0·330 = ... − 0·996........
m	− 0·376 = ... − 0·853........
n	− 0·376 = ... − 0·595........
o	− 0·381 = ... − 0·332........
p	− 0·399 = ... + 0·166........
q	− 0·397 = ... + 0·564........
r	− 0·426 = ... + 0·892........
s	− 0·452 = ... + 0·987........

The sum of all the equations gives

$$-7{\cdot}018 = 18\left(\frac{\text{H}}{\text{I} \cos \delta} + \tan \delta \,.\, \text{N}\right) + 1{\cdot}745 \,.\, (\text{P} - \text{M}).$$

The sum of all, changing the signs of those from *g* to *p*, gives

$$-0{\cdot}632 = +11{\cdot}411 \,.\, (\text{P} - \text{M}).$$

From these,

$$\text{P} - \text{M} = -0{\cdot}055, \quad \frac{\text{H}}{\text{I} \cos \delta} + \tan \delta \,.\, \text{N} = -0{\cdot}386.$$

Again, expressing each of the values of $\frac{\text{disturbing force to starboard}}{\text{I} \cos \delta}$ by the formula

$$\frac{\text{S}}{\text{I} \cos \delta} + (\text{P} + \text{M}) \sin \text{A},$$

we have the following equations.

Reference to observation.	Equation.
a	$+ 0{\cdot}345 = \frac{\text{S}}{\text{I} \cos \delta} + 0{\cdot}171 \,.\, (\text{P} + \text{M})$
b	$+ 0{\cdot}387 =$ .... $+ 0{\cdot}391$........
c	$+ 0{\cdot}385 =$ .... $+ 0{\cdot}539$........
d	$+ 0{\cdot}403 =$ .... $+ 0{\cdot}739$........
e	$+ 0{\cdot}416 =$ .... $+ 0{\cdot}856$........
f	$+ 0{\cdot}428 =$ .... $+ 0{\cdot}981$........
g	$+ 0{\cdot}396 =$ .... $+ 1{\cdot}000$........
h	$+ 0{\cdot}332 =$ .... $+ 0{\cdot}927$........
i	$+ 0{\cdot}413 =$ .... $+ 0{\cdot}485$........
k	$+ 0{\cdot}318 =$ .... $+ 0{\cdot}142$........
l	$+ 0{\cdot}290 =$ .... $- 0{\cdot}086$........
m	$+ 0{\cdot}211 =$ .... $- 0{\cdot}523$........
n	$+ 0{\cdot}243 =$ .... $- 0{\cdot}804$........
o	$+ 0{\cdot}233 =$ .... $- 0{\cdot}943$........
p	$+ 0{\cdot}242 =$ .... $- 0{\cdot}986$........
q	$+ 0{\cdot}229 =$ .... $- 0{\cdot}826$........
r	$+ 0{\cdot}277 =$ .... $- 0{\cdot}451$........
s	$+ 0{\cdot}267 =$ .... $- 0{\cdot}159$........

The sum of all the equations gives

$$+ 5{\cdot}815 = 18 \cdot \frac{\text{S}}{\text{I} \cos \delta} + 1{\cdot}453 \,.\, (\text{P} + \text{M}).$$

The sum of all, changing the signs from *k* to *s*, gives

$$+ 1{\cdot}195 = + 10{\cdot}725 \, (\text{P} + \text{M}).$$

From these,

$$\text{P} + \text{M} = + 0{\cdot}111, \quad \frac{\text{S}}{\text{I} \cos \delta} = + 0{\cdot}314.$$

and

$$\text{M} = 0{\cdot}083, \quad \text{P} = 0{\cdot}028.$$

The permanent magnetic force may therefore be represented by the force

$$\sqrt{\{\overline{0{\cdot}386}^2 + \overline{0{\cdot}314}^2\}} = 0{\cdot}50,$$

inclined to the ship's keel at an angle whose tangent $= \frac{-314}{386}$. In compounding this, for the different positions of the ship, with the terrestrial force, it is to be observed that the diminution 0·08 is too serious to be neglected (as we have hitherto done), and that 0·92 must therefore be considered as measuring the terrestrial force. With these numbers the effect of the permanent magnetism is computed graphically as before; and the result, and its comparison with the observed disturbance, are contained in the following Table.

Reference to observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.	Reference to observation.	Azimuth of ship's head.	Observed disturbance of compass.	Computed disturbance of compass.	Disturbance yet to be accounted for.
	° ′	° ′	° ′	° ′		° ′	° ′	° ′	° ′
a	9 50	−28 20	−27 20	−1 0	*k*	171 50	+16 0	+16 10	−0 10
b	23 0	−22 30	−18 0	−4 30	*l*	184 55	+10 55	+11 45	−0 50
c	32 35	−11 20	− 7 30	−3 50	*m*	211 30	− 0 40	+ 2 30	−3 10
d	47 40	+ 6 40	+10 0	−3 20	*n*	233 30	− 6 20	− 5 5	−1 15
e	58 55	+16 50	+20 45	−3 55	*o*	250 35	−11 50	−11 0	−0 50
f	78 40	+28 50	+30 45	−1 55	*p*	279 35	−20 20	−20 30	+0 10
g	89 0	+35 0	+32 25	+2 35	*q*	304 20	−25 20	−27 20	+2 0
h	112 0	+27 10	+31 30	−4 20	*r*	333 10	−30 30	−32 30	+2 0
i	151 0	+25 30	+22 30	+3 0	*s*	350 50	−29 20	−30 0	+0 40

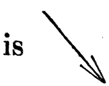
From the value of P above, the residual term ought to have for maximum value 1°·6, supposing the permanent magnetism not to act at the same time; in simultaneous action the maximum would be nearly doubled in the first quadrant (from the weakening of the terrestrial force by the permanent magnetism), and would be diminished by one-third in the third quadrant; the signs would be − + − + in the four quadrants. The agreement of the signs and magnitudes of the residual terms with those defined by this law is extremely close; the value for observation *h* alone presenting a sensible disagreement. The theory, therefore, may be considered as perfectly in accordance with the facts observed in the deviations and intensities at the position of this compass.

The maximum of the term depending on P being (when the permanent magnetism is counteracted) 1°·6, it was thought unnecessary to encumber the binnacle with a mass of iron for the correction of that small quantity. The only correction applied was a magnet, placed below the compass, in a position making the angle whose tangent is $\frac{-314}{386}$ with the ship's keel, and at a distance at which its effect (as found by trial on shore) was 0·50 of the earth's directive force, or produced a deviation of 27° nearly when transverse to the meridian. The deviation of the compass was then found to be as follows.

Azimuth of ship's head.	Disturbance of compass.
° ′	° ′
3 15	+1 30
45 45	−1 15
94 45	−1 45
182 45	−0 45
224 0	−2 30
276 20	+0 40
323 0	−2 30

The whole of these apparent disturbances are within the limits of errors of observation; it is difficult to say whether they contain any distinct trace of the inductive term.

Another compass in the same ship (a tell-tale, or compass suspended to a beam

in the cabin) was observed in regard to deviation only. The observations were made by an incompetent person, and are not worth transcribing. The maximum deviation was greater than that at the binnacle. But this singular circumstance presented itself: that the deviation vanished when the azimuth of the ship's head was 140° and 320° nearly, the maximum + error occurring near azimuth 200°, and the maximum — error near azimuth 80°. At the binnacle compass, the deviation vanished in azimuths 40° and 220° nearly, and its maximum + and — errors occurred in azimuths 90° and 340° nearly. Therefore, to make the direction of the ship's independent magnetism at the tell-tale parallel to the magnetic meridian, it was necessary to turn the ship 100 degrees further than was necessary to effect the same for the binnacle compass. Or, supposing the head of the ship towards the top of the page, the direction of the magnetic force (as acting on the marked end of the needle) is  at the binnacle, and  at the tell-tale. These stations are not, if I remember right, more than twelve feet apart. In the Rainbow, the directions of the forces on the four compasses were represented by lines as  or , all included within a small portion of the same quadrant.

The correction of this compass (the tell-tale) was effected by a tentative method, which is likely to be of the highest value in the correction of the compasses of iron ships in general. The ship's head being placed exactly north, as ascertained by a shore compass, a magnet was placed upon the beam from which the compass was suspended, with the direction of its length exactly transverse to the ship's keel: it was moved upon the beam to various distances till the compass pointed correctly, and then it was fixed. Then the ship's head was placed exactly east; and another magnet with its length parallel to the ship's keel was placed upon the same beam, and moved to different distances till the compass pointed correctly, and then it was fixed. The correction for induced magnetism was neglected: but there would have been no difficulty in adjusting it by the same process, placing the vessel's head in azimuth 45°, or 135°, or 225°, or 315°. The peculiar advantage in the method above given, as a tentative method, consists in this: that the magnetic action is resolved into two parts, either of which can be altered without at all disturbing the other, and that by a very simple rule those positions of the ship can be found in which each of these parts is effective while the other is powerless. The same remark applies to the correction for induced magnetism.

The Ironsides has since that time sailed to Pernambuco, and her compasses have been correct (as far as general observation goes) through the voyage. It is probable, therefore, that the constant N is not very large: but no accurate observations have been yet reported to me upon which any certain statement as to that point can be founded.

Section VIII.—*Concluding Remarks.*

It appears from the investigations above, that the deviations of the compass at four stations in the Rainbow, and at two stations in the Ironsides, are undoubtedly caused by two modifications of magnetic power; namely, the independent magnetism of the ship, which retains the same magnitude and the same direction relatively to the ship in all positions of the ship; and the induced magnetism, whose force varies in magnitude and direction while the ship's position is changed. It appears also that, in the instances mentioned, the effect of the former force greatly exceeds that of the latter.

It appears also that experiments and investigations similar to those applied above, are sufficient to obtain with accuracy the constants on which, at any one place, the ship's action upon the horizontal needle depends (namely, $\frac{H}{I\cos\delta}+\tan\delta\,.\,N$, $\frac{S}{I\cos\delta}$, M, and P); and that by placing a magnet so that its action will take place in a direction opposite to that which the investigations show to be the direction of the ship's independent magnetic action, and at such a distance that its effect is equal to that of the ship's independent magnetism, and by counteracting the effect of the induced magnetism by means of the induced magnetism of another mass (according to rules which are given), the compass may be made to point exactly as if it were free from disturbance.

It appears also that by an easy tentative method, the compass may now be corrected without the labour of any numerical investigations, or any experiments, except those of merely making the trials.

It appears also that the permanent vertical disturbing force, as far as the examination of the Rainbow authorizes us to draw any distinct conclusion, is not great, and therefore that there is no fear of great disturbance of the compass by the heeling of the ship.

But it appears that one of the magnetic constants consists of two parts, which cannot be separated by experiments on the horizontal magnet at any one place; and that the effect of the impracticability of separating these parts will be, to render the compass incorrect in one magnetic latitude when it has been made correct in a different magnetic latitude (though there is good reason to think that the term on which the variation depends is so small that it may be neglected, except in the case of a ship sailing very near the magnetic pole). And it appears that though in theory the term in question could be determined from observations of the dipping-needle, yet in practice the method fails, because the observations cannot be made with the requisite accuracy. It appears, however, that this term may be determined by observations of the horizontal needle at two places whose magnetic latitudes are different, and that the correction may then be made perfect for all magnetic latitudes.

To these considerations we may add the following: that though the uniformity of

the induced magnetism, under similar circumstances, is to be presumed, yet the invariability of the independent magnetism during a course of many years is by no means certain.

These statements suggest the following as rules which it is desirable to pursue in the present infancy of iron-ship building.

1. It appears desirable that every iron sea-going ship should be examined by a competent person, for the accurate determination of the four constants,

$$\frac{H}{I \cos \delta} + \tan \delta \,.\, N, \qquad \frac{S}{I \cos \delta}, \qquad M, \qquad \text{and } P,$$

for each of the compasses in the ship; and that a careful record of these determinations should be preserved, as a magnetic register of the ship.

2. It appears desirable that the same person should examine the vessel at different times, with the view of ascertaining whether either of the constants changes with time.

3. It appears desirable that in the case of vessels going to different magnetic latitudes, the same person should arrange for the examination of the compasses in other places, with a view to the determination of N.

4. It appears desirable that the same person should examine and register the general construction of the ship, the position and circumstances of her building, &c., with the view of ascertaining how far the values of the magnetic constants depend on these circumstances, and in particular to ascertain their connexion with the value of the prejudicial constant M.

5. It appears desirable that the same person should see to the proper application of the correctors, and the proper measures for preserving the permanency* of their magnetism.

The most remarkable result, in a scientific view, from the experiments detailed above, is the great intensity of the permanent magnetism of the malleable iron of which the ship is composed. It appears, however, that almost every plate of rolled iron is intensely magnetic. In the progress of the investigations I have endeavoured to make some experiments with plates of iron, for the purpose of examining the induced magnetism of iron plates in different states of connexion, but they have failed totally, in consequence of the amount of independent magnetism. On placing a compass within a large cylinder of iron plate, whose axis was horizontal and in the magnetic meridian, I was surprised to see that the deviation of the compass was as great as at the binnacle position in the Rainbow.

The scrolls of iron used for correcting the induced magnetism in the Rainbow were repeatedly passed through the fire before their permanent magnetism was destroyed. In some which were tried, even this process was ineffectual. I am disposed to prefer

* The magnets which I have fixed in the Rainbow and the Ironsides have been heated to a temperature of 120° FAHR., with their marked ends towards the south, and have afterwards stood vertically with their marked ends upwards for one or two days. For mounting in the ship they have been let into grooves in pieces of wood, in which they have been bedded in tallow.

for correctors boxes filled with iron chain; for though many parts of the chain may possess some independent magnetism, yet it is likely that there will be, to a great extent, an intermutual destruction of effects.

If we conceive permanent magnetism to depend upon an artificial arrangement of the particles of the metal, the manufacture of rolled iron seems to account in some degree for this amount of magnetism. The iron, after leaving the puddling furnace, is rolled out into bars of considerable length; these are broken, and their pieces are laid side by side, and the united pieces are again rolled out, &c. The whole object of the manufacture is to arrange the particles in that artificial state known by the name *fibre*.

It is believed by practical men that the state of malleable iron changes from time only. If this be certain, and if the notion just mentioned be plausible, it seems sufficiently probable that the independent magnetism of the ship will change with time. This consideration enforces strongly the necessity of periodical examination as suggested above. Such examination may possibly have an advantage beyond the correction of the compass for the time. An important change in the magnetism may indicate an important alteration in the quality of the iron, and may serve as a warning to be cautious of trusting to the strength of the ship in critical circumstances.

I know not whether the axis of magnetism in a plate of iron may be expected probably to coincide with the direction in which it has been extended by rolling. The direction of the horizontal magnetism in the Rainbow (conceiving the transverse part to be produced by the transversal partitions or bulk heads), and the insignificant amount of the vertical magnetism, seem to countenance this supposition. The great difference between the magnetism of the two compasses in the Ironsides may seem, perhaps, to place difficulties in the way of such a supposition.

Royal Observatory, Greenwich,
April 9, 1839.